



LIBRARY
UNIVERSITY OF CALIFORNIA
DAVIS



STATE OF CALIFORNIA
The Resources Agency
Department of Water Resources

BULLETIN No. 116-4

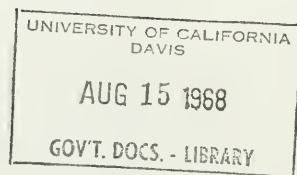
EARTHQUAKE ENGINEERING PROGRAMS

Progress Report

MAY 1968

RONALD REAGAN
Governor
State of California

WILLIAM R. GIANELLI
Director
Department of Water Resources



LIBRARY
UNIVERSITY OF CALIFORNIA
DAVIS

STATE OF CALIFORNIA
The Resources Agency
Department of Water Resources

BULLETIN No. 116-4

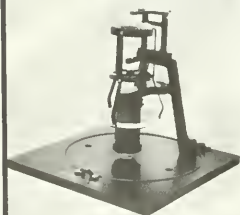
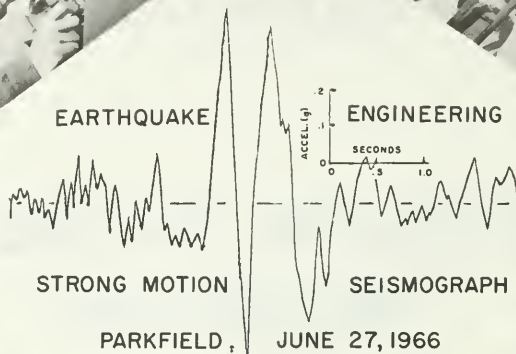
EARTHQUAKE ENGINEERING
PROGRAMS

Progress Report

MAY 1968

RONALD REAGAN
Governor
State of California

WILLIAM R. GIANELLI
Director
Department of Water Resources



ABOUT THE FRONTISPIECE

The frontispiece shows earthquake engineering activities of the Department. Seismology and geodesy disciplines are highlighted. The drawing in the center is of a seismogram recorded by one of the strong-motion seismographs referred to in the Foreword; during the Parkfield earthquakes, the seismograph documented the most intense ground shaking ever recorded in a California earthquake. Reading clockwise from right center, the photographs show a strong-motion seismograph, the Oroville seismic vault, a stretch of the California Aqueduct, a mounted thermistor for temperature sensing in precise electro-optical measurement of crustal movement with the Geodimeter, a seismoscope, adjustment of the Geodimeter, a kytoon for mid-line temperature recording of Geodimeter lines, and a reflex prism for reflection of Geodimeter light.

FOREWORD

The earthquake engineering programs of the Department of Water Resources are described in this bulletin. These programs are defined as those developed to provide information on earthquake and ground movements near the State Water Project, the hazards which these may pose to Project structures, and criteria for use in design and operation of Project facilities which will minimize or eliminate the effects of such hazards. The present earthquake engineering programs encompass the earlier Crustal Strain and Fault Movement Investigation and other design-oriented programs.

The programs represent a number of firsts. Among them:

They are the first comprehensive programs for systematically collecting and analyzing seismic, geodetic and other data specifically for use in locating and designing large hydraulic structures.

They are the first pursued by a centralized organization staffed with the necessary specialties of seismology, engineering, geodesy and engineering geology.

They include the first large group of strong-motion seismographs ever operated by a state government. The strong-motion instruments along the planned route of the Coastal Branch of the California Aqueduct recorded the June 1966 trio of earthquakes near Parkfield and provided engineers with the first instrumental data ever available on how the intensity of shaking diminishes with distance from an earthquake fault.

They include the first regular monitoring of both gradual and abrupt crustal movements along major fault systems. Monitoring of gradual movement shows great promise in distinguishing between active and inactive faults and some prospect of earthquake prediction.

The Department believes that an interdisciplinary approach to earthquake engineering problems is necessary to serve the growing statewide needs brought about by an increasing density of population and construction in areas of high seismic risk.

William R. Gianelli

William R. Gianelli, Director
Department of Water Resources
State of California
March 21, 1968

TABLE OF CONTENTS

	<u>Page</u>
ABOUT THE FRONTISPIECE	iii
FOREWORD	v
ORGANIZATION, DEPARTMENT OF WATER RESOURCES	xi
ORGANIZATION, CONSULTING BOARD FOR EARTHQUAKE ANALYSIS	xii
ACKNOWLEDGMENT	xiii
ABSTRACT	xiv
I. INTRODUCTION	1
Safety of the State Water Project	1
Department Responsibility	3
II. SUMMARY	5
Data Collection and Analysis	6
Earthquake Data	6
Sensitive Seismographs	6
Mobile Seismic Laboratories	8
Strong-Motion Seismographs	9
Seiche Recorders	9
Data on Gradual Tectonic Movement	10
Distance Measurement with the Geodimeter	11
Fault Zone Triangulation	12
Fault Movement Quadrilaterals	12
Tiltmeters	12
Data on Other Gradual Movements	13
Preconstruction Geodetic Control	13
Subsidence Leveling	13
Landslide Monitoring	14
Earthquake Hazard and Engineering Criteria	14
Hazard Reports	14
Development of Engineering Criteria	15
Theoretical Design Earthquakes	15
III. COLLECTION AND ANALYSIS OF SEISMIC DATA	17
Epicenter Determination	17
Sensitive Seismograph Network	17
Oroville Network	18
San Luis Station	21
Cedar Springs Station	21
Jamestown Observatory	24
Portable Seismographs	26
Epicenter File	29
Analysis of Department Seismic Data	32
Ground Motion	33
Mobile Seismograph Laboratories	33
Strong-Motion Seismographs and Seismoscopes	38
Seiche Recorders	46
Special Instrumentation for Oroville Dam	47
Stress Cells	48
Pore Pressure Cells	51
Accelerometers	53
Analysis of Historical Earthquake Damage	57

TABLE OF CONTENTS
(Continued)

	<u>Page</u>
IV. COLLECTION AND ANALYSIS OF TECTONIC DATA	61
Geodimeter Measurements	63
New Developments	74
Earthquake Prediction	77
Fault Zone Triangulation	82
Fault Movement Quadrilaterals	91
Tiltmeters	95
V. COLLECTION AND ANALYSIS OF DATA ON OTHER EARTH MOVEMENTS	101
Precise Leveling	101
Subsidence Leveling	101
Control Leveling	104
San Pedro-San Francisco	104
Gorman to Cedar Springs Reservoir Site	109
Vicinity Tehachapi Tunnels	110
Precise Leveling for Upper Eel River Development	111
Landslide Monitoring	112
VI. EARTHQUAKE HAZARD AND ENGINEERING CRITERIA	113
Earthquake Hazard Reports	114
Engineering Criteria	119
Development of the Program	120
Strength and Deformation Characteristics of Soils Under Earthquake Loading	122
Response of Embankments to Dynamic Loading	124
Examination of Contemporary Design Techniques and Previous Embankment Failures	127
Studies in Progress	129
Increased Capability of the Finite Element Embankment Design Program	129
Improved Methods of Computation of Lateral Soil Pressures on Rigid Structures	129
Cracking Potential in Earthfill Dams	130
Specialized Training	130
Estimates of Earthquake Strong-Motion (Design Earthquakes)	131
Field Evaluation of Earthquakes	139
Hebgen Lake, Montana, Earthquake, 1959	139
Hollister Earthquake, 1961	139
Alaska Earthquake, 1964	140
Corralitos Earthquake, 1964	140
Seattle Earthquake, 1965	140
Truckee Earthquake, 1966	140
Earthquake Notification	141
Emergency Plan	141

TABLE OF CONTENTS
(Continued)

	<u>Page</u>
VII. OTHER EARTHQUAKE PROGRAMS IN CALIFORNIA	143
University of California at Berkeley	143
The University of California at Los Angeles	144
The University of California at La Jolla	145
California Institute of Technology	145
Stanford University	146
Other State Agencies	146
Office of Architecture	146
Division of Mines and Geology	147
Federal Agencies	147
Coast and Geodetic Survey	147
Geological Survey	148
Earthquake Mechanism Laboratory	149

FIGURES

<u>Number</u>		<u>Page</u>
1	Geologic Hazards and the State Water Project	2
2	Typical Seismic and Geodetic Investigation for the State Water Project	7
3	State Water Project Sensitive Seismograph Network.	19
4	Oroville Seismograph Network.	20
5	Oroville Seismograph Station.	22
6,7	Cedar Springs Seismograph.	23
3	Portable Seismograph	27
9	Portable Seismograph Stations	28
10	Seismic Analysis Center: Control Modules	30
11	Seismic Analysis Center: Film Viewer and Instruments.	30
12	Mobile Seismograph Investigation Sites	34
13	Spectral Ratio Curves for Wheeler Ridge	37
14	Strong-Motion Seismograph.	39
15	Strong-Motion Seismograph Stations.	40
16	Seismoscope	41
17	Strong-Motion Seismograms, Parkfield Earthquake	44
18	Seismoscope Records.	45
19	Dynamic Instrumentation in Oroville Dam	49
20	Installation of Stress Cells in Oroville Dam	52
21	Installation of Carlson Dynamic Pore Pressure Cell	54
22	Triaxial Accelerometer.	56
23	Earthquake Damage Frequency	53
24	Location of Hydraulic Structures Damaged by Earthquakes, 1865-1966	60

FIGURES
(Continued)

<u>Number</u>		<u>Page</u>
25	Annual California Fault Movement, 1959-1965 . . .	65
26	Field Equipment for Geodimeter Measurements . . .	67
27	Geodimeter Light Reflector	68
28	Geodimeter Mercury Arc Lamp Adjustment	68
29	Computer Output of Twelve Geodimeter Readings for a Single Line Measurement	69
30	Crustal Movement, Hollister-Parkfield Area . . .	72
31	Computer Output Summarizing Five Years of Measurement of Two Lines	73
32	Crustal Movement Resurvey, Parkfield Earthquake . .	75
33	Crustal Movement and Corralitos Earthquake . . .	79
34	Crustal Movement and Earthquakes, Cholame Area . .	81
35	Location of DWR-USC&GS Cooperative Triangulation Projects	83
36	T-3 Theodolite	85
37	Observation Tent and Instrument Stand	85
38	Lightkeeper at Triangulation Station	85
39	Bilby Steel Tower	85
40	First-Order Triangulation, Sandberg to Wheeler Ridge	86
41	Fault Zone Triangulation, Vicinity of Gorman . . .	87
42	First-Order Triangulation, Upper Eel River Development	89
43	Fault Zone Triangulation, Taft-Mojave Area . . .	90
44	Typical Fault Movement Quadrilaterals	93
45	Fault Movement Quadrilaterals near Aqueduct Crossings	94
46	Typical Tiltmeter Installation	98
47	Tiltmeter Construction	99
48	Tiltmeter Locations	100
49	Subsidence Leveling for the State Water Project . .	102
50	Land Subsidence Along California Aqueduct, Los Banos-Kettleman City Area	105
51	Geodetic Control Program, Precise Leveling for State Water Project	106
52	Computer-Plotted Locations of Earthquake Damaged Hydraulic Structures	116
53	Computer Output of Stored Data on Earthquake Damaged Structures	117
54	Earthquake Hazard Reports	118
55	Ground Displacement vs. Distance from San Andreas Fault	133
56	Shear Strain, Vicinity of San Andreas Fault . . .	133
57	Average Acceleration Spectra Curves	135

STATE OF CALIFORNIA
THE RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES

RONALD REAGAN, GOVERNOR
William R. Gianelli, Director, Department of Water Resources
John R. Teerink, Deputy Director

STAFF AND SERVICES MANAGEMENT

Wesley E. Steiner Assistant Chief Engineer
Meyer Kramsky Chief, Technical Support

This report was prepared under the direction
of

Renner B. Hofmann Supervisor, Earthquake Engineering Office
by

David M. Hill Program Manager, Earthquake Data Analysis
John H. Bennett Program Manager, Earthquake Data Collection

Assisted by

Roger C. Martin Associate Engineering Geologist
John E. Wolfe Associate Engineering Geologist
Clyde E. Renz Assistant Engineering Geologist
James A. Pell Assistant Engineering Geologist
Paul W. Morrison Associate Seismologist

With special guidance and assistance from

Laurence B. James Chief Geologist and Coordinator of
Seismic Investigations
Raymond C. Richter Supervising Engineering Geologist

Material on seismic design procedures and research was
reviewed by the Division of Design and Construction.

CONSULTING BOARD FOR EARTHQUAKE ANALYSIS

California Department of Water Resources is advised and its earthquake programs are guided by its Consulting Board for Earthquake Analysis.

DR. CLARENCE R. ALLEN, Chairman*

Associate Professor of Geology and Geophysics,
California Institute of Technology, Pasadena.
Mechanics of faulting; relation of seismicity to
geologic structures; tectonics of Southern
California and Baja California, Mexico.

DR. GEORGE W. HOUSNER

Professor of Civil Engineering and Applied
Mechanics, California Institute of Technology,
Pasadena. Engineering seismology; structural
dynamics; aseismic design.

DR. H. BOLTON SEED

Professor of Civil Engineering,
University of California, Berkely.
Soil mechanics; foundation and embankment stability.

MR. N. D. WHITMAN, JR.**

Whitman, Atkinson, and Associates,
Consulting Engineers, Pasadena and San Diego.
Structural analysis; design of hydraulic structures.

DR. JAMES L. SHERARD

Woodward, Clyde, Sherard, and Associates,
Consulting Engineers, Oakland and New York.
Design of earth and rockfill dams.

Dr. John A. Blume, civil and structural engineer, and Dr. Bruce A. Bolt, seismologist, joined the Consulting Board for Earthquake Analysis subsequent to the compilation of this report.

*The late Dr. Hugo Benioff was Chairman of the Consulting Board until his retirement on November 15, 1965, at which time Dr. Allen became Chairman.

**Deceased December 14, 1966.

ACKNOWLEDGMENT

The late Dr. Hugo Benioff, Seismologist, Professor Emeritus of the California Institute of Technology, was Chairman of the Department's Consulting Board for Earthquake Analysis until his retirement in the fall of 1965. To him and the other members of the Board we owe a special debt for their guidance, help and encouragement.

The U. S. Coast and Geodetic Survey, under a cost-sharing agreement with the Department, has provided technical assistance and personnel to install and operate sensitive and strong-motion seismograph instruments, analyze seismic records, and accomplish major geodetic surveys. The U. S. Coast and Geodetic Survey, San Francisco Seismological Field Survey Office, under the direction of Mr. W. K. Cloud, has provided much assistance for the seismic program.

The University of California at Berkeley, through contracts with the Department, has programs which are producing results of major importance. Programs under the direction of Dr. H. Bolton Seed involve development of engineering criteria and design procedures for soils structures, and model testing of embankment dams. Programs under the direction of Dr. Bruce Bolt provide rapid notification of earthquakes via the University's telemetered seismograph network augmented by the Department's Jamestown station, analysis of seismograms, and assistance in the development of earthquake data retrieval systems.

We are indebted to many, for information and assistance, particularly those associated with the U. S. Naval Testing Facility at China Lake, California, the U. S. Geological Survey, and the Earthquake Mechanism Laboratory of the United States, Environmental Science Services Administration.

ABSTRACT

Earthquake and ground movement engineering data are obtained by the Department of Water Resources for use in the design and operation of the State Water Project. They include information from instruments such as sensitive and strong-motion seismographs, tiltmeters, and seiche recorders and information derived from geodetic surveys. These surveys provide measurements of fault movement (both strain and creep), changes in fault movement rate preceding earthquakes, rates of subsidence in areas of concern to the State Water Project, and fault creep at those locations where the State Water Project must cross active faults. These data can be applied to the development of new design criteria. The efforts to collect, analyze and determine methods of using these data comprise the Department of Water Resources' Earthquake Engineering Programs. They represent a major State effort in coping with earthquakes. As a result of these programs, the California State Water Project will be safer and more reliable.

CHAPTER I. INTRODUCTION

Adequate water supplies and adequate flood control throughout the State have long concerned Californians. Major steps were taken to solve these problems when the Legislature enacted the Water Development Act in 1959 and authorized bonds in 1960 to finance the largest, most comprehensive water storage and conveyance system ever constructed.

Safety of the State Water Project

Facilities of the State Water Project will extend over half the length of California. Examples of safety problems caused by ground movement are illustrated in Figure 1 and are discussed below.

1. Relatively small earthquakes near dams or remote reaches of aqueducts may initiate embankment failures or earth slides into the reservoirs or the aqueducts. For example, during the 1964 Alaskan earthquake, relatively low intensity shaking (VI on the Mercalli scale) triggered large slides that caused catastrophic destruction. Earthquake frequency is of concern because the State Water Project is so close to the highly active San Andreas fault.

2. Bigger earthquakes are certain to affect portions of the State Water Project. It will be subject to more severe earthquakes than would any similar project in any other state.

3. The California Aqueduct and its branches must cross some of the most active faults in North America in more than half a dozen places. The necessity of these crossings is clear -- it is impossible to build an aqueduct from the Sacramento-San Joaquin Delta to Perris reservoir without, as the map shows, crossing the San Andreas fault. Fault movement, whether or not it generates an earthquake, could breach the aqueduct.



4. Regional tilting in amounts previously observed, whether caused by tectonic uplift or by subsidence induced by man, could affect the operation of the very large Project pumps.

5. Subsidence would affect especially the low gradient -- less than four inches in a mile -- of the California Aqueduct. Subsidence in excess of 25 feet has been recorded in the San Joaquin Valley. Because of economic and aqueduct grade requirements, routing through subsiding areas is unavoidable.

Department Responsibility

The Department of Water Resources has been authorized to plan, design, construct, and operate the State Water Project. The assignment carries with it the responsibility for the integrity of the Project when it is shaken or disrupted by an earthquake or other ground movement that may reasonably be expected during its lifetime. This concern is prompted by the monetary value of the Project and the water, by the Department's delivery obligations, and by the potential hazards to adjacent populations posed by structures holding back a total of 6.8 million acre-feet of water.

The Department's responsibility for the integrity of not only the State Water Project but also other water facilities in the State is a statutory one. Section 6081 of the California Water Code directs the Department to "... take into consideration the possibility that a dam or reservoir might be endangered by seepage, earth movement, or other conditions" (Underlining added.) This is the only such authority vested in any state agency. Section 227 empowers the Department, in siting facilities, to "... investigate any natural situation available for reservoirs or reservoir systems"

Ground movement problems are considered by the Department in each stage of Project development and implementation, from planning, through design and construction and into operation of the State Water Project. The Department also has service agreements with the University of California at Berkeley for research into earthquake-resistant engineering. Section 12064 of the Water Code empowers the Department to "... correspond, confer, and cooperate with the United States, its departments or agencies" The Department does this under a cost-sharing Federal-State Cooperative Agreement for Geodetic Surveys and Seismological Investigations with the U. S. Coast and Geodetic Survey, which performs data collection and analysis work in cooperation with the Department for programs of mutual interest to the State and Federal Governments.

CHAPTER II: SUMMARY

The Department formally began programs to supply engineering data to cope with ground movement problems in 1958. The Consulting Board for Earthquake Analysis was first convened early in 1962. The Board recommended a course of action that has resulted in the three present Earthquake Engineering programs.

- Data Collection
- Data Analysis
- Earthquake Hazard and Engineering
- Criteria Program

The Data Collection and Analysis programs have two broad continuing objectives in solving the problems described above. They are:

1. To warn of increased probability of hazard or damage by monitoring, both before and after construction:
 - a. Earthquakes
 - b. Gradual fault movement and its relation to earthquakes
 - c. Tectonic tilting
 - d. Subsidence
 - e. Earth sliding

2. To determine expected earthquake ground motion for the State Water Project and other sites where the Department has responsibility.

In the Hazard and Criteria Program, analyzed data are evaluated in hazard reports for specific Water Project sites and design criteria are developed in which actual earthquake motions are considered.

The Data Collection program is a field crew operation including equipment installation, maintenance and geodetic observations. Crew scheduling and logistics are of principal concern. The Data Analysis program requires skills in such areas as mathematics, computers, electronics

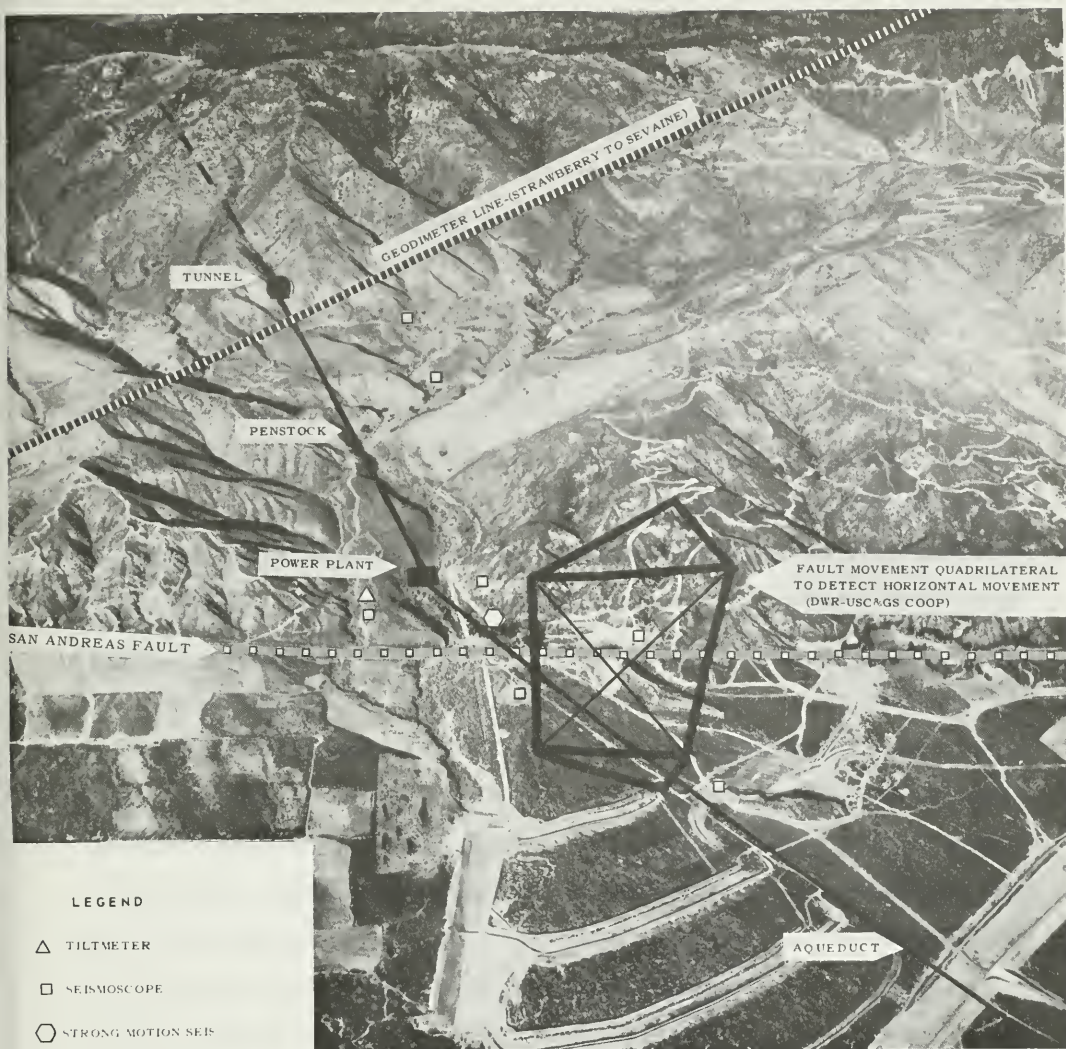
and report production. In this bulletin, both data collection and analysis are described together to provide a coherent picture of each activity. These are grouped into categories of seismic, tectonic and other earth movement data. This area of work is generally concerned with results from instrumentation. Examples at a Water Project facility site are in Figure 2.

Data Collection and Analysis

Earthquake Data

Earthquake data needed for the planning, design, and operation of the State Water Project include not only those concerned with the frequency and locations of earthquakes but also those dealing with earthquake motions and the response of Project sites and facilities to them. The Department obtains the first group of data with sensitive seismographs and the second with mobile seismic laboratories and strong-motion seismographs. Seiche recorders determine the behavior of enclosed bodies of water.

Sensitive Seismographs. The Department plans to install sensitive seismographs near and around each major dam or group of dams. Use of these networks will permit determination of epicenters of the smallest of local temblors. Epicenters are points on the surface of the earth directly above abrupt movements. The smallest earthquakes, not felt by humans, may cause no visible damage to facilities; but the record of their epicenters may indicate the existence of an active fault. It has been claimed that such displacements may have been involved in the erosion under Baldwin Hills Reservoir at Los Angeles, which led to its failure in 1963. An epicenter alignment could be a cue for intensive inspection of a dam.



The above represents a critical segment of the California Aqueduct at Devil Canyon, near San Bernardino.

Creep along the San Andreas fault is detected by periodic resurveys of the "quadrilateral". General crustal movement is monitored by similar resurveys of much larger networks using a Geodimeter. One line from such a network is shown in the upper part of the figure. Tectonic and local earth tilting is monitored by the tiltmeter. Seismoscopes and the strong-motion seismograph record directional components and accelerations of moderate and strong earthquakes, used as criteria in designing earthquake-resistant structures.

Figure 2. TYPICAL SEISMIC AND GEODETIC INVESTIGATION FOR THE STATE WATER PROJECT

A seismograph network at Oroville Dam is now in full operation. Here the embankment is completed. Other proposed seismograph installations are shown in Figure 3. Some of the installed seismographs are operated cooperatively with the University of California at Berkeley or the U. S. Coast and Geodetic Survey.

This seismograph network will cover the entire Project from Oroville to Perris reservoir. It will complement the existing systems of the University of California at Berkeley and California Institute of Technology; and greatly increase the overall capability for monitoring earthquakes in California. It can be combined with the existing systems and readily augmented by the addition of a few strategically located stations to completely cover the entire State. Such a statewide net would be of great benefit to the Department in discharging its responsibility for safety of dams, since it would enable the rapid and accurate location of epicenters of all earthquakes that occurred in the State.

Mobile Seismic Laboratories. Seismographs can, of course, do more than find epicenters. Analyses of the seismograph records provide a direct indication of how much the ground under the instrument has vibrated in response to earthquakes. Ground shaking at State Water Project sites is measured by the Department's two mobile seismic laboratories, operated as a pair. One is placed on the construction site foundation material and the other on a nearby hard rock site. Both labs record several seismic events. Comparison of the seismograms provides an estimate of how much greater ground motion during a major earthquake can be expected at the construction site, compared with a hard rock site. With this information, the earthquake resistant design of structures can be improved.

This activity is a cooperative program with the U. S. Coast and Geodetic Survey.

Strong-Motion Seismographs. The mobile labs, like the networks, consist of sensitive instruments which cannot always record the heavy, reverberating ground motion that follows the larger earthquakes. Strong-motion seismographs record this information at construction sites. They are triggered only by severe motion. Thirty-one strong-motion seismographs have been installed at State Water Project sites.

Larger earthquakes are, of course, rarer than smaller ones, so the strong-motion instruments operate only when triggered by a significant earthquake. The four instruments near the planned route of the Coastal Branch Aqueduct, for example, recorded intense ground shaking in response to a moderate shock in 1966.

Strong-motion seismographs will also be operated in Project facilities as they are completed, to measure structural response to strong ground motion. These data will indicate whether the structure may have been stressed beyond its designed limits and, if so, warn engineers that thorough inspection and testing, and perhaps repair or even redesign, are necessary for continued assurance of safety. This activity is a cooperative program with the Coast and Geodetic Survey.

Seiche Recorders. Large earthquake vibrations, particularly those that arrive last at some distance from the epicenter, can cause water to oscillate in reservoirs. If the water waves are generated in concert with the arriving vibrations and if this resonance is maintained for a time, the water may overtop the reservoir. These resonant oscillations are called seiches. In the Alaskan earthquake of 1964, some seiches were so violent

that large trees along shores were broken or uprooted. Such damage occurred for example on the shores of Kenai Lake, 60 miles south of Anchorage. (U. S. Geological Survey, "The Alaskan Earthquake, Regional Effects", Professional Paper 543-A, 1966.) This lake covers an area of about 30 square miles and has a depth of 135 feet, dimensions like those of some State Water Project reservoirs.

The best way to determine the natural period of a reservoir is to measure the amplitude, or energy level, of its water waves when the reservoir is disturbed by small earthquakes, high winds, or passing weather fronts. Theoretical determination of seiche energy levels in an irregularly shaped reservoir is very difficult. The need for measurement has led to development of a prototype instrument that records the energy levels of water waves. The machine was tested intermittently in San Pablo Reservoir, Contra Costa County, with the permission of the East Bay Municipal Utility District.

Data on Gradual Tectonic Movement

Most California earthquakes result from abrupt displacement underground, without noticeable surface fracture. But often gradual movement takes place along a surface fault trace, the rocks being slowly displaced or distorted by tectonic forces without earthquakes that can be felt.

If gradual slippage is occurring where an aqueduct must cross a fault, special designs can be incorporated to reduce repairs. Wherever feasible, aqueduct facilities cross known currently active faults at the surface rather than in tunnels, to facilitate repairs. Concrete-lined canals can be supplemented with an impervious earthfill lining, which, because of its self-sealing properties, will reduce leakage caused by a breach, and pipe joints can be articulated. The latter method was used where the South Bay Aqueduct crosses the Hayward fault, Figure 1.

Rock bending at fault-aqueduct crossings is somewhat more difficult to detect. The important consideration is that the bending means strain is accumulating in the rocks, possibly foreshadowing an earthquake and sudden fault displacement which could sever the aqueduct. Intensive monitoring of strain accumulation is clearly called for at these crossings.

The Department has measured gradual tectonic movement in four ways: with a Geodimeter, fault quadrilaterals, tiltmeters, and by triangulation.

Distance Measurement with the Geodimeter. Most fault movement in California is horizontal. Gradual movement that could disrupt the State Water Project has been monitored since 1959, detected directly by measurement of changes in the distance between permanent monuments located on either side of an active fault. Distances are measured periodically with a Model 2A Geodimeter, based indirectly on the time it takes a pulsed beam of light to leave the instrument at one monument, reflect from a mirror at the other monument, and return. More than 2,000 miles of such lines are measured annually. Along the San Andreas fault, for example, where the coastal side moves northward with respect to the continental side, the average annual movement generally diminishes from a maximum of four centimeters near Hollister, Figure 30, to no measurable movement near Los Angeles.

A byproduct of this activity has been the discovery that sudden strain release may be more likely along a segment of the fault where the movement rate differs from that of adjacent areas or from its past rate; for the first time, there is some prospect of earthquake prediction. In order to fully explore this possibility, it would be necessary both to increase the frequency of observations and to extend the program to cover all major active faults in California. Furthermore, improved instrumentation such as the dual-laser technique would have to be developed to increase accuracy of measurement

and enable observations to be made under less than ideal atmospheric conditions.

Fault Zone Triangulation. Since 1959 the Department has participated with the Coast and Geodetic Survey in the reobservation of existing triangulation and the establishment of new networks in critical areas. These networks provide precise Project survey control and a basis for determination of ground movements when reobserved in the future.

Fault Movement Quadrilaterals. This activity is carried on at locations where the aqueduct crosses active faults. Geodimeter measurement does not distinguish between movement due to fault slippage and that due to strain, primarily because the lines measured are long, from 8 to 20 miles. Measurements over much shorter lines -- 250 to 500 meters in length -- provide indication of slippage. These lines, arranged in quadrilaterals, are measured with upgraded geodetic techniques. The quadrilaterals are measured in cooperation with the U. S. Coast and Geodetic Survey.

Tiltmeters. Gradual crustal movements in California are both horizontal and vertical. Crustal uplift and subsidence in sedimentary material result in some tilting at the surface, which, over a long term, could pose serious problems at pumping plants and along the aqueduct, which carries water along a grade of less than four inches per mile. Tilting of a few degrees could cause an increase in required pump repair. To forestall this eventuality, the Department determines amounts of tilting at pumping plant sites before completing pump designs. Six tiltmeters at pumping plant sites have provided this information in a few months. They detect tilting of 39 millionths of an inch along a 100-foot horizontal line.

Data on Other Gradual Movements

Ground movements, whether caused by tectonic forces associated with earthquakes or by other forces, are monitored by the same techniques and pose similar hazards to the State Water Project. Consequently, monitoring of ground movement regardless of cause, sometimes indeterminable, is a part of the Earthquake Engineering program.

The surface of the earth can move, very gradually, in response to nontectonic forces. Geodetic networks measure this movement. One of the most serious of these phenomena, as far as the Project is concerned, is subsidence caused by agricultural and industrial activity. Another is gradual sliding of hillsides above water resources developments.

Preconstruction Geodetic Control. Construction surveys for the State Water Project must be tied to recent and precise geodetic measurements. Once established, geodetic networks provide a secondary benefit in that they can be used for future measurements of ground movement from tectonic or other causes. The Department has cooperated with the U. S. Coast and Geodetic Survey in establishing and upgrading geodetic networks in the vicinity of Project facilities. This cooperation has resulted in mutual benefits and economies.

Subsidence Leveling. California is almost unique in the United States in experiencing shallow subsidence in large areas of its valleys. When certain soils in the San Joaquin Valley are irrigated, they compact. In deep subsidence, withdrawal of ground water and oil can lead to subsidence of the ground surface. The State Water Project must transverse some of these subsiding regions. To effect solutions to the engineering problems involved, the Department must know the extent and rate of subsidence. The Department's

leveling program to determine this information is a cost-sharing cooperative with the U. S. Coast and Geodetic Survey.

The availability of water carried by the Aqueduct to previously dry areas is likely to have a profound effect on shallow subsidence. Recharge and withdrawal of water from deep aquifers may also change and consequently influence deep subsidence. These anticipated changes will in turn affect the State Water Project as well as other structures. By monitoring, these changes can be detected and corrective steps taken before loss of efficiency or damage occurs. Monitoring of subsidence will be needed in many areas served by the Aqueduct.

Landslide Monitoring. Potentially hazardous landslides are a subject of concern in the planning of proposed dam and reservoir sites in the secluded North Coast region, Figure 9, scheduled to be tapped next as a major supply to meet California's increasing water needs. Some of these hillsides are still moving, though so gradually that the movement can only be detected by precise survey techniques or refined instrumentation. Several critical slides are currently being monitored in the Upper Eel River Development area.

Earthquake Hazard and Engineering Criteria

Hazard Reports

Reports have been made on earthquake hazards at 23 critical facility sites. A typical report contains:

1. Appraisal of known faults
2. Number of recorded earthquakes
3. History of damage
4. Distance from major faults

5. Estimate of the intensity of the strongest shock expected.
The latter estimate is based on the type of foundation rock at the site. Vibration intensity, or shaking is measured in terms of the rapid acceleration and deceleration of the ground and is expressed in units of gravity (one g indicates that the maximum acceleration in shaking is 32 feet per second/per second).

At times, reports have contributed to Department decisions to relocate or reduce the size of facilities--for example, Airpoint Dam. See Pages 115 and 118.

Development of Engineering Criteria

In 1962, the Department's Consulting Board for Earthquake Analysis recommended several areas of earthquake engineering research for protection of the State Water Project. Although this research was not all completed in time for use in Project design, much of the new knowledge is being used to test conventional design procedures that are the basis for most Project construction.

At least two of the studies have already yielded major results. One is failure criteria for saturated sand, based on the number of earthquake pulsations, overburden and pore pressures, degree of saturation, degree of compaction, and composition. These new criteria at times produce results differing from those obtained by conventional methods. Another major advance is a computer program designed to provide the distribution of internal stresses in earthfill structures when two components of expected earthquake motion are known. With further development, this program promises to become a completely defined generalized design procedure for embankments.

Theoretical Design Earthquakes

The response of structures on different foundation materials has proven surprisingly varied. In general, structures not specifically designed

for earthquake loadings have fared far worse on soft saturated alluvium than on hard rock, implying that the alluvium is responsible for more violent vibration.

Only two significant strong-motion seismograms have been recorded that are of value to structural engineers in California. Consequently, there is little information on the degree of shaking to be expected on different geologic foundations. In 1962, the Department's Consulting Board for Earthquake Analysis recommended that the Department determine what kind of shaking could be expected at major facility sites, and this can now be done with theoretical equations derived in recent years from research in seismology. The product is a theoretical seismogram commonly referred to as a design earthquake.

The Department's pair of mobile seismograph laboratories supply data concerning the effect of specific geologic foundations on earthquake shaking. With these data, the Department can refine theoretical design earthquakes for specific Project sites. However, acquiring the needed data and making the required computations take time. To avoid delays to the State Water Project and to meet the Department's urgent need for earthquake factors for use in design of Project structures, the Consulting Board for Earthquake Analysis prepared for the Department a family of average earthquake acceleration curves which have general applicability.

CHAPTER III: COLLECTION AND ANALYSIS OF SEISMIC DATA

Epicenter Determination

Sensitive Seismograph Network

Sensitive seismograph installations are planned for each major dam or group of dams in the State Water Project. Sites are selected so instruments will be on solid foundations where seismic noise is minimal. The network will permit detection of small, local earthquakes, even those too small to be felt by humans. These may cause no immediately detectable damage to facilities, but the alignment of their epicenters may indicate stress-induced adjustments on faults. Adjustments on hidden faults or fracture zones beneath a dam or abutment could result in leakage, which might lead to failure. Adjustments in slide masses or along bedding planes have preceded more catastrophic movements. These events have been blamed for major disasters involving dams and reservoirs. A landslide behind the Vaiont Dam in Italy displaced tons of water, which inundated and virtually destroyed the village of Vaiont. Fault displacements ultimately resulted in piping that led to the failure of the Baldwin Hills Reservoir in 1963.* A line of epicenters beneath a dam or reservoir could be a cue for intensive inspection of the facilities.

Dams, perhaps more than any other type of facility, would cause widespread secondary damage if they failed. For this reason, stations are being installed especially to record small earthquakes near dams.

Telemetry of data from all the stations to Sacramento for centralized recording is planned. Telemetry of data from other operational

*Department of Water Resources. "Investigation of Failure, Baldwin Hills Reservoir", April 1964, Page 3.

sensors of the Project, like water level sensors, is now carried on in completed portions. Complete telemetry from all the Department's seismic stations to Sacramento would be more economical than the installation of duplicate housing and recording and exact timing apparatus at each station. With instantaneous notice of seismic events, delay in inspection and repair or operational changes, if needed, would be minimized.

Figure 3 shows the locations of stations of the sensitive seismograph network. Three at Oroville Dam are already in full operation. Single stations are operating at San Luis and Cedar Springs. Because pumping and dam facilities are relatively close together within the Pyramid-Castaic and Cedar Springs-Perris areas, the facilities can be covered by three stations.

A description of the instrumentation at Oroville, San Luis and Cedar Springs follows. The link between the Department's Jamestown seismograph and the seismic network of the University of California at Berkeley is also discussed.

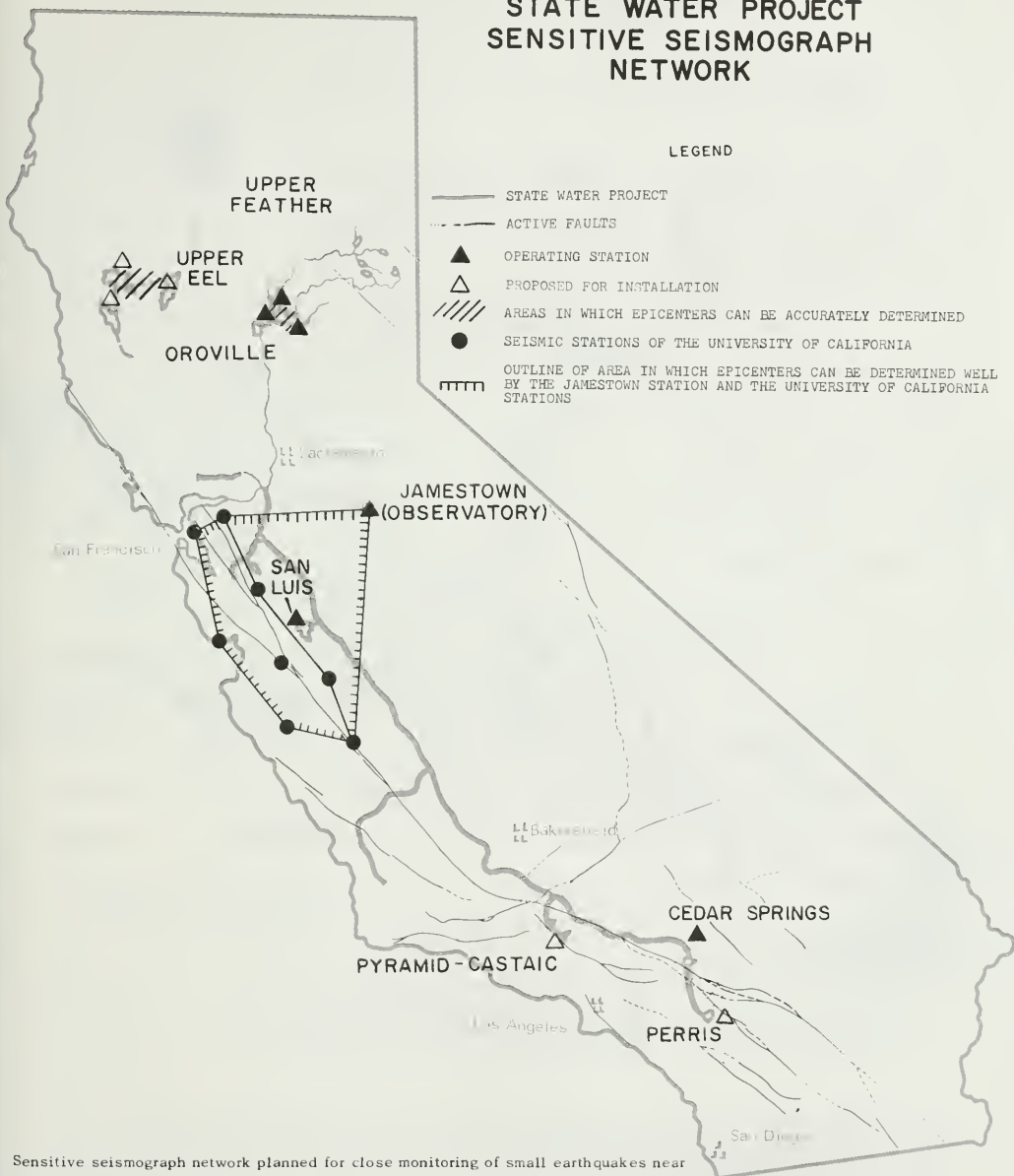
Oroville Network. The central station in the Oroville network is one-half mile north of the right abutment of Oroville Dam. Construction was completed in July 1963 and the station began operating in August. A geophysicist from the U. S. Coast and Geodetic Survey (USC&GS) is permanently stationed there as part of the Department's cooperative agreement with that agency. Station components conform to specifications of worldwide standardized stations.

Network operation began when two auxiliary vertical seismographs were installed in May 1966 (Figure 4). Their data are telemetered to the central station and epicenters can be determined within an accuracy of about a kilometer. The short-period instruments, with a magnification of about 150,000 at one cycle per second, will react to small but significant local shocks.

STATE WATER PROJECT SENSITIVE SEISMOGRAPH NETWORK

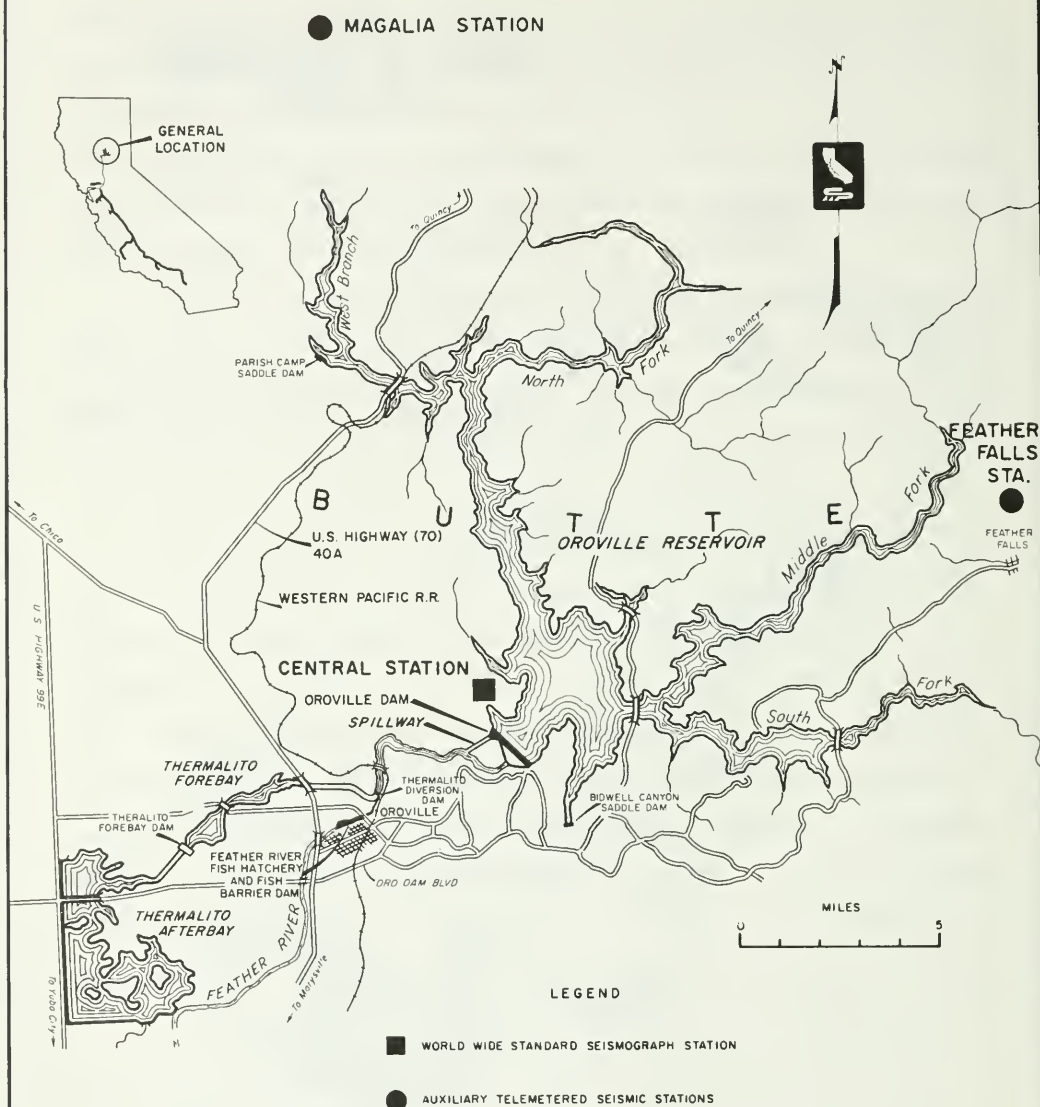
LEGEND

- STATE WATER PROJECT
- - - ACTIVE FAULTS
- ▲ OPERATING STATION
- △ PROPOSED FOR INSTALLATION
- //// AREAS IN WHICH EPICENTERS CAN BE ACCURATELY DETERMINED
- SEISMIC STATIONS OF THE UNIVERSITY OF CALIFORNIA
- ||||| OUTLINE OF AREA IN WHICH EPICENTERS CAN BE DETERMINED WELL BY THE JAMESTOWN STATION AND THE UNIVERSITY OF CALIFORNIA STATIONS



Sensitive seismograph network planned for close monitoring of small earthquakes near State Water Project dams. These events, far more numerous than strong earthquakes, could eventually open cracks and allow piping beneath earth embankments.

SCALE OF MILES
0 50 100



Sensitive seismographs are used to determine the pre-construction level of seismicity in the Project area, to monitor ground shaking caused by blasting during construction, and to record post-construction changes in seismicity related to filling and emptying of the reservoir. A minimum of three stations is required to pinpoint epicenters of earthquakes beneath the dam and reservoir.

OROVILLE SEISMOGRAPH NETWORK

Recording equipment is shown in Figure 5.

San Luis Station. This station is in the Coast Range near Pacheco Pass west of San Luis reservoir. Instrument output is telemetered to recording facilities at the construction field office. This area is marked by considerable seismicity.

There are three short-period seismometers with magnification between 65,000 and 100,000. A fourth seismometer operates at a gain of 3,000 to ensure that records of large, closeby shocks will be available if they should disable the more sensitive equipment.

This station was installed by the USC&GS under contract with the U. S. Bureau of Reclamation. The Department shared the cost of the station as part of the San Luis project. Specifications were coordinated with the Department and were prepared by Dr. George Rouse of the U. S. Bureau of Reclamation in Denver, Colorado. The Department will assume responsibility for operating the station upon completion of the San Luis project.

Cedar Springs Station. This station consisting of a portable seismograph at a temporary site within the proposed Cedar Springs reservoir, is located about 50 miles east of Los Angeles at the north edge of the San Bernardino Mountains. It was installed in February 1965 and instrumentally upgraded through contract with the USC&GS. The station has adequate sensitivity to monitor seismic activity in the Cedar Springs area and along the San Andreas fault in the vicinity of the Devil Canyon Powerplant, Figure 34. Its magnification is currently about 50,000. In the near future, the Cedar Springs station will be moved to a permanent location and linked with the rest of the network by telemetry.

The instrument shown in Figure 6 consists of three short-period, 14 kg Benioff seismometers, 0.2 second galvanometers, and a 4-channel, 35 mm film recorder. Records are changed daily and sent to the U. S. Coast and Geodetic Survey, Seismological Field Survey Office, San Francisco, for



Recording vault. The large drums hold photographic paper on which light beams are reflected by the mirror galvanometers at the left. The seismometers (not shown) are in a "quiet" location in a nearby underground vault.

Figure 5. CROVILLE SEISMOGRAPH STATION

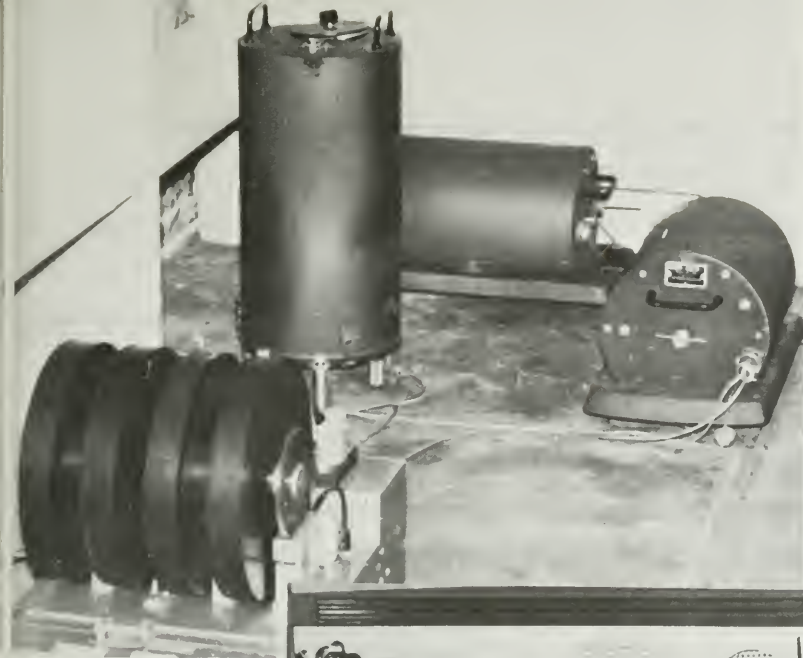


Figure 6

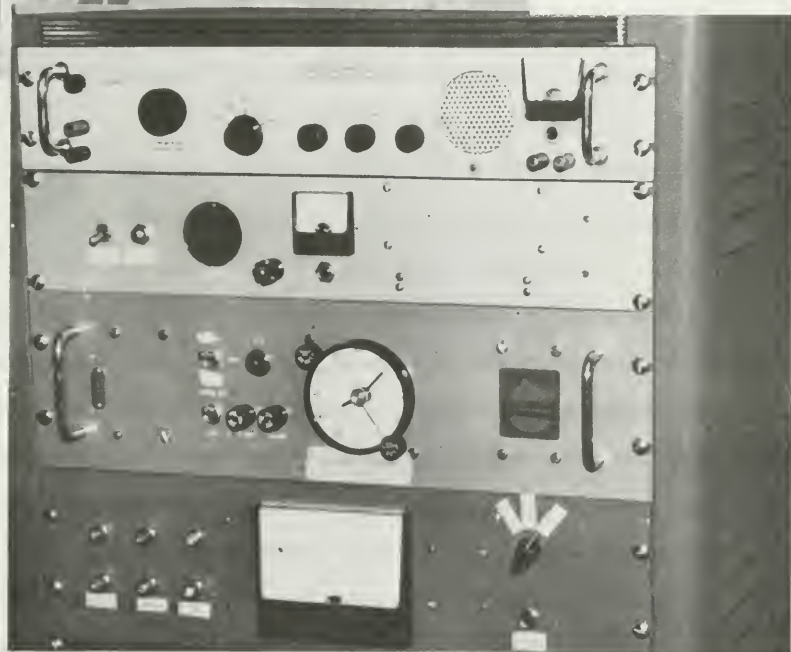


Figure 7.

Four-drum film recorder and Benioff seismometers. The seismometers are oriented to detect the north-south, east-west, and vertical components of ground motion.

Control module with WWV radio and clock to produce precise time marks on seismograms.

CEDAR SPRINGS SEISMOGRAPH

inspection and then to Rockville, Maryland, for copying and analysis. The station control rack is shown in Figure 7.

An unusually large number of very small shocks has been recorded in this region. The Coast and Geodetic Survey, in quarterly reports to the Department, listed over 450 earthquakes within a 50 km radius of Cedar Springs Dam site during the first year of operation. The range of magnitudes was 1 to 5.5, but only 28 shocks had magnitudes of over 2.5. (Richter magnitudes are used exclusively in this report.) These and related data have been presented at consulting board meetings convened to consider the safety and stability of this damsite. The Department's Earth Dams Consulting Board and the Consulting Board for Earthquake Analysis have used these data in making recommendations concerning design features of the Cedar Springs facility.

Monitoring of seismic activity in this area will be continued. The longer the record of earthquake activity, the more accurate will be interpretations of the tectonic pattern near planned water facilities.

Jamestown Observatory. This station near the town of Sonora, in the seismically quiet Sierra, stands apart from the State Water Project damsite network, Figure 3, Page 19. It is the most sensitive station in Northern California and is operated cooperatively with the University of California at Berkeley. Shocks of magnitude smaller than 0.2 originating in the San Francisco Bay area are recorded at Jamestown. The Berkeley seismic network is to the west of the Project, Jamestown to the east. The combination of Jamestown and the Berkeley net straddles the northern portion of the California Aqueduct to greatly improve determinations of epicenters near San Luis Dam and the northern reaches of the aqueduct system. The Jamestown-Berkeley net is sensitive enough to monitor earthquakes over much of the length of the

California Aqueduct. The area in which epicenters may be determined with increased accuracy is outlined in Figure 3. There are or will be Project facilities in both segments.

The Jamestown seismograph station is equipped with three of the Department's short-period 100 kg Benioff seismometers. These were installed in an adit of the old Harvard Mine in the summer of 1964 under an agreement with the University of California at Berkeley.

Characteristics of these larger Benioff units are the same as those of the worldwide seismograph system. Complete records are changed daily and mailed to Berkeley each week for interpretation. The magnification of the system at one cycle per second is 200,000.

An additional short-period 14 kg vertical Benioff seismometer was installed a year later; its output is telemetered to Berkeley. Its record and the records of the other stations of the Berkeley network are displayed on 16 mm film. Its peak response is at a shorter period than for the other Jamestown seismographs and it has a magnification of 500,000.

With the addition of the Jamestown station, the Berkeley network can determine epicenters along northern reaches of the Aqueduct about three times more accurately than was previously possible. An alignment of epicenters along the Aqueduct was recently recorded, suggesting a hidden fault along the eastern base of the Coast Range.

The Seismographic Station at Berkeley informs the Department monthly of all earthquakes within 20 miles of the Aqueduct which are also within the area covered by the University of California stations, Figure 3.

The damsite seismographs described above are planned for post-construction seismic monitoring. Filling of reservoirs will undoubtedly

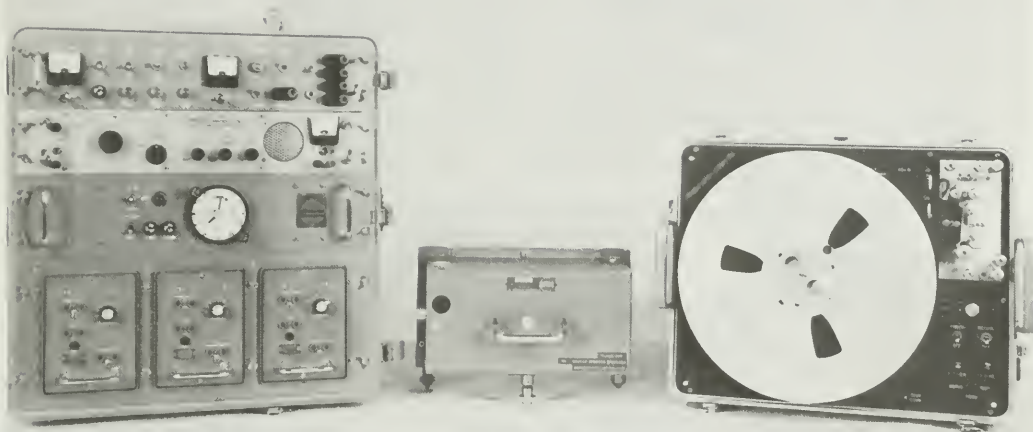
affect the seismic behavior of underlying geologic foundations, and, to measure this effect accurately, the Department should know foundation behavior before filling. The Oroville network is doing this job for small local earthquakes. The effect of filling is of special interest at San Luis Reservoir because of the unusual geology of the reservoir area. Adding to the necessity of determining preconstruction seismicity is the need to fix epicenters at sites as a guide to designers where design time remains.

Portable Seismographs

Lacking completed permanent networks at other Project sites, the Department uses sensitive portable seismographs, which monitor on magnetic tape before and during construction. Components of a portable system are shown in Figure 8. These short-period instruments were acquired in the spring of 1966. As shown in Figure 9, two were recently installed at two sites in the Cedar Springs area and the third has been operating in the Upper Eel watershed since April 27, 1966. A permanent sensitive seismograph is planned for each major facility.

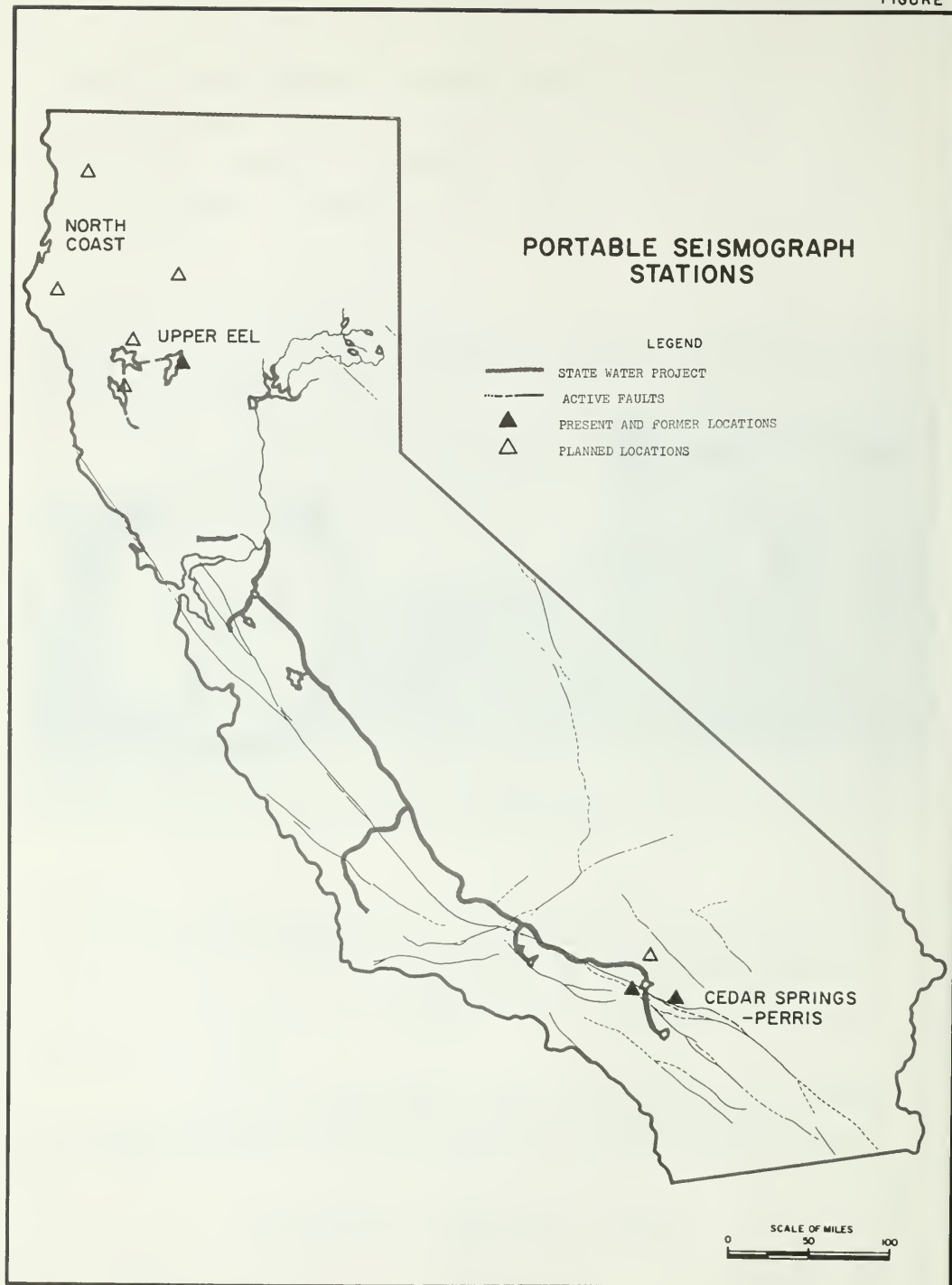
Three more portables were purchased in 1967. One will replace the existing observatory at Cedar Springs, since the equipment at the station is somewhat cumbersome for routine analysis. The other two new instruments will service the Upper Eel sites; together with the portable seismograph already there, they can monitor the area that is likely to become California's next major source of water.

As a part of the Department's North Coastal Investigation for Water Resources Development, still another triplet of portable equipment has been



Timing and control unit is at left. Center unit is one of three seismometer components. Magnetic tape recorder, right, can operate unattended up to 30 days.

Figure 8. PORTABLE SEISMOGRAPH



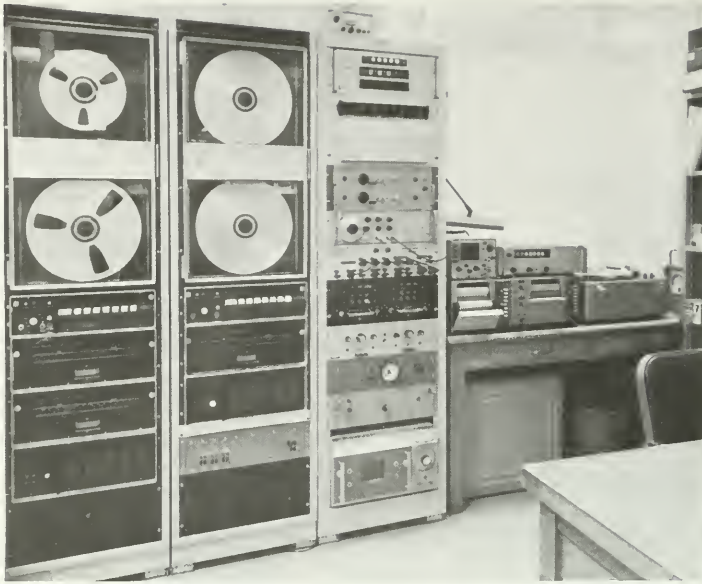
acquired for study of the Klamath and Trinity River areas, as shown in Figure 9. These areas have a level of seismic activity as high as any in the State. This equipment is designed to telemeter data rather than record at the site on magnetic tape, to avoid costly field maintenance in this relatively rough and undeveloped area. Most of the high-maintenance components can be operated at an analysis center in Sacramento where calibration and repair can be performed easily.

Components of the Seismic Analysis Center presently comprise two tape recorders and associated electronic equipment, which will receive the telemetered North Coast signals and play back both telemetered data and data recorded at the site on magnetic tape. Another instrument continuously makes and displays a film copy of the telemetered seismogram and a film viewer is available for later intensive analysis of the seismogram. These components are shown in Figures 10 and 11. The telemetry itself is not yet in operation.

Epicenter File

Earthquake epicenter information is collected and maintained for all instrumentally determined earthquakes in and near California. The resulting data file provides a source of rapidly available information for preparation of hazard reports for Project facilities. The data have been used, for example, in:

1. The Earthquake Epicenter and Fault Map of California
2. Seismic hazard evaluation reports
3. Seismic probability studies
4. Earthquake energy release studies
5. Responses to special requests for earthquake data



SEISMIC
ANALYSIS CENTER,
SACRAMENTO

Figure 10. CONTROL MODULES



Figure 11. FILM VIEWER INSTRUMENTS

In 1960, the Department obtained decks of computer punched cards containing epicenter data from the California Institute of Technology and the U. S. Navy's China Lake Ordnance Test Center. These data originally came from station bulletins published by the University of California, the California Institute of Technology, and the U. S. Coast and Geodetic Survey. The program has been possible because of the cooperation of the California Institute of Technology and University of California at Berkeley, which together supplied most of the original data, much of it already on punched cards. They contained epicenter locations, date, time, quality of location, and magnitude for the years 1934-1957. The cards were merged and collated to provide a complete set of epicenter information through 1957. Since 1960, the deck has been updated periodically to include data through 1962. Preliminary data for the years 1963, 1964, and 1965 are available. Two additional historical earthquake data files are available. The University of California at Berkeley has a catalog of California earthquakes covering the period before 1934, and the University of Nevada has a similar catalog of earthquakes for the State of Nevada.

The data file provided information for completion of a fault and earthquake epicenter map depicting over 2,000 epicenters and 3,000 faults. Automation of the data retrieval system including plotting will reduce by several man-weeks the time required to prepare hazard reports.

Prior to the implementation of this program, there was no complete, accessible, statewide record of earthquake epicenters. Earthquake data have been available only in separate, chronologically arranged quarterly lists.

Analysis of Department Seismic Data

Seismograms from the Department's Oroville network and Jamestown seismograph station are processed and analyzed for the Department by the seismograph station at the University of California at Berkeley. The University combines the data from those stations with data from its own network in computing the locations of seismic events near State Water Project facilities and throughout California. The University seismograph station notifies the Department by telephone when earthquakes larger than Magnitude ⁴ are recorded. The information on these events is immediately relayed to appropriate units in the Department. Summaries of earthquakes and construction blasts near Oroville reservoir and the California Aqueduct are sent to the Department each month. The summaries are included in memoranda on earthquake activity which are distributed throughout the Department. Microfilm copies of seismograms periodically are forwarded to the Department. The original records from Oroville are forwarded to the USC&GS.

Seismograms from the DWR-USBR San Luis seismograph station and from the DWR Cedar Springs station are processed and analyzed by the USC&GS. Lists of earthquake epicenters in the Cedar Springs-Devil Canyon area are forwarded to the Department each month.

The magnetic tapes from the portable sensitive seismographs are converted to visual records at the Department's playback center. These records are used in analysis of seismic activity and for special investigations in the Project areas where the portable seismographs are located. Analog to digital conversion of the magnetic tape seismograms for input to the computers is planned as a part of the permanent seismic monitoring equipment.

Ground Motion

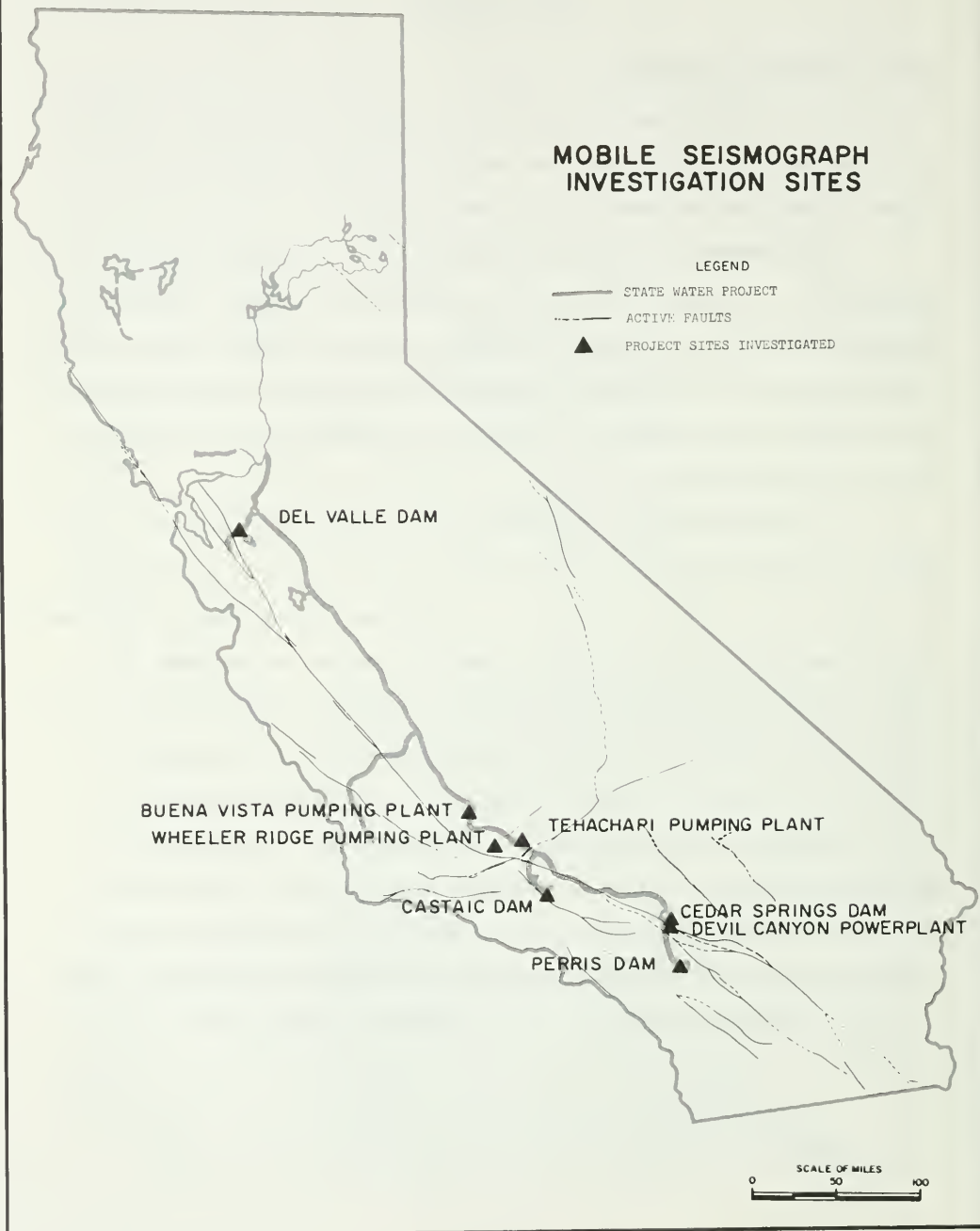
Mobile Seismograph Laboratories

Two mobile seismograph laboratories were acquired in 1964 to study the earthquake response of foundation materials at State Water Project sites. Project sites being investigated are shown in Figure 12.

That damage is generally greater on soft, weak material than it is on hard rock is well known. In "Reviews in Engineering Geology" (edited by Thomas Fluhr and Robert F. Legget, Geological Society of America, 1962, p. 167), Frank Neumann reports that some investigators have estimated vibration displacements on water-soaked alluvium to be 30 times as great as those on adjoining outcrops of basement rock.

The Department has, of course, avoided soft foundations where possible. But effective aseismic design nonetheless requires vibration estimates at Project sites, estimates that have not previously been available. The ground spectral amplification factor is determined by comparing spectra from earthquakes recorded simultaneously at two stations situated on different foundations. One seismograph laboratory is installed on the foundation of the site to be tested and the other on a nearby hardrock outcrop. An average of several spectral ratios is made for each major construction site. The amplification factor and related ground acceleration may differ from these estimates for very intense shocks when foundation materials no longer behave elastically. Consequently, transfer functions between strong-motion records and small shocks recorded by mobile seismographs at strong-motion seismograph sites are being developed.

The ground spectral amplification program using mobile seismographs was recommended to the Department by the Consulting Board for Earthquake



Analysis in 1962. The USC&GS shares, on a matching fund basis, the cost of operating the instruments and processing the records. Measurements have been made at the sites of Wheeler Ridge, Tehachapi, and Buena Vista Pumping Plants and of Del Valle, Castaic, Cedar Springs, and Perris Dams and Devil Canyon Powerplant. Results of local and distant shocks and, at times, nuclear blasts at the Nevada test site are used to provide a broad range of frequencies. Computations made from the records require at least three well-recorded earthquakes between 3.5 and 5.0 magnitude and located within 200 to 300 miles of the site being tested. Usually, sufficient data are recorded in 6 to 16 weeks at each site.

Each mobile seismograph includes three short-period, 14 kg Benioff seismometers with one-second galvanometers, and recorders operated at three times the normal speed. These components are calibrated to obtain identical response characteristics. Maximum gain of the mobile stations is usually limited to about 5,000 by foundation site ambient noise. Magnetic tape recorders and ancillary equipment recently were installed under the DWR-USC&GS cost-sharing program. Use of magnetic tape will permit automatic digitization, which will have obvious advantages.

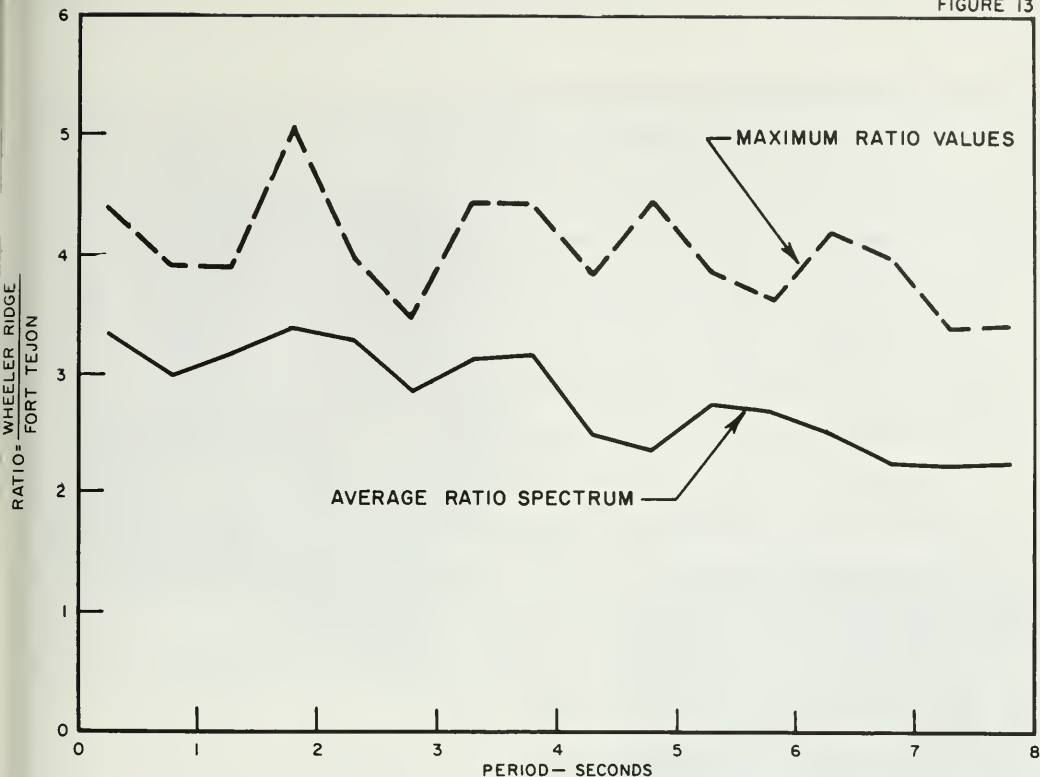
Currently, the records are manually digitized by the USC&GS, which uses an approximation procedure developed at the California Institute of Technology. Fourier spectra are computed with a computer program also developed at the California Institute of Technology by A. G. Brady.

Investigation of the spectral characteristics of geologic foundation materials at proposed Water Project facility sites began at Wheeler Ridge in August 1964. One mobile laboratory was placed near Wheeler Ridge Pumping Plant No. 1, the other on bedrock at Fort Tejon seven miles away. Eight earthquakes suitable for analysis were recorded. The earthquake records were

digitized, and a Fourier analysis of the data was made by the USC&GS. The average ratios between spectrum values for the eight shocks are shown on Figure 13. The maximum ratios between the spectra of pairs of the shocks are also shown.

Seismograms recorded at other sites have been digitized by the USC&GS but Fourier analyses of the spectra have not been computed. Pending completion of the spectral analyses, the USC&GS has provided the Department with average amplitude ratios by direct scaling and comparison of the seismograms from Project sites with those from bedrock sites. These summaries are shown below.

AMPLITUDE RATIOS		
<u>Dates of Seismograms</u>	<u>Amplitude Ratio Estimated Manually from Each Seismogram</u>	<u>Average Amplitude Ratio</u>
Tehachapi Pumping Plant (on Tejon Sandstone) Hardrock site: Ft. Tejon (on granite)		
3-26-65	1.01	1.3
4-21-65	1.63	
5-7-65	1.23	
Buena Vista Pumping Plant (on alluvium) Hardrock site: Mt. Abel (on granite)		
6-16-65	2.17	2.2
6-17-65	1.57	
7-23-65 5:32 a.m.	2.35	
7-23-65 5 p.m.	3.01	
7-27-65	1.94	
Del Valle Damsite (at Patterson Ranch, on sandstone) Hardrock site: Los Mochos Arroyo (on graywacke)		
11-15-65	2.37	2.5
12-3-65	2.6	
Castaic Damsite (on sandstone) Hardrock site: Warm Springs (on granitics)		
3-12-66	2.87	3
3-18-66	3.86	
3-19-66	2.2	



Spectral ratio curves indicate the expected (computed) magnification of earthquake shaking of a foundation on alluvium as opposed to one on bedrock nearby. The data are obtained by analysis of simultaneous earthquake recording by two identical seismographs, one on a Project site, and the other on crystalline bedrock. In this case, the Department's mobile seismic trailers were used, one at the Wheeler Ridge Pumping Plant site, and the other at Fort Tejon in the Tehachapi Mountains, 7 miles away.

The curves provide design engineers with a basis for deriving ground acceleration (g) factors for use in earthquake-resistant design of structures for the tested sites.

Figure 13. SPECTRAL RATIO CURVES FOR WHEELER RIDGE
(After - USC & GS)

Strong-Motion Seismographs and Seismoscopes

Thirty-one strong-motion seismographs have been installed at State Water Project facility sites to provide data regarding ground response to major earthquakes. See Figures 14 and 15. The balance of the Department's strong-motion seismograph network will be installed in the facilities themselves as they are completed, to determine structural response to ground response. The instruments record ground accelerations for the type of foundation material on which they have been installed. Records from the Department's strong-motion arrays and network also indicate the rate of attenuation of earthquake waves with distance from active faults during a large earthquake. This information cannot be obtained from sensitive instruments because these are usually rendered inoperative during major earthquakes.

Seismoscopes (Figure 16) indicate the occurrence and direction of ground motion during an earthquake without reference to time. A horizontal pendulum records the earthquake motion on a smoked watch glass. Seismoscopes are placed in the vicinity of each seismograph, usually on different types of foundation materials so that their responses to earthquake waves can be compared. These are low-cost instruments.

The instruments are purchased and maintained under the cooperative agreement with the USC&GS. Department personnel select sites, and provide housing and power facilities where needed. Thermoelectric generators fueled by bottle gas provide electricity where public power is unavailable.

Locations of strong-motion seismographs are:



Front and rear views of the Teledyne Model AR-240 strong-motion recorder--a portable, three-component seismograph for recording acceleration during strong local seismic disturbances. These instruments are coming into wide use as permanent installations in large buildings and dams.

Figure 14. STRONG-MOTION SEISMOGRAPH





The instrument is designed to provide records of the expected response of average structures under strong local seismic shocks. Strong motion is recorded mechanically by means of a simple scribe on a smoked watchglass.

Figure 16. SEISMOSCOPE

<u>Strong-Motion Seismograph Stations</u>	<u>Number of Satellite Seismoscopes</u>
Frenchman Dam, Plumas Co.	4
Oroville Dam, Butte Co.	5
Franciscan Dam Site, Mendocino Co.	1
Spencer Dam Site, Mendocino Co.	1
Dos Rios Dam Site, Mendocino Co.	1
Newville Dam Site, Glenn Co.	0
San Luis Dam (W/USBR), Merced Co. (2 units)	2
Orestimba Creek Crossing, Merced Co.	4
Del Valle Dam Site, Alameda Co.	4
Delta Pumping Plant, Contra Costa Co.	4
Empire Tract, San Joaquin Co.	1
Polonio Pumping Plant, Kern Co.	3
Coastal Branch Array, San Luis Obispo Co. (4 units)	12
Buena Vista Pumping Plant, Kern Co.	3
Wheeler Ridge, Kern Co.	4
Fort Tejon, Kern Co.	0
Castaic Reservoir, Los Angeles Co.	7
Elizabeth Lake Array, Los Angeles Co. (4 units)	12
Devil Canyon Powerplant, San Bernardino Co.	7
Tehachapi Pumping Plant, Kern Co.	2
Oso Pumping Plant, Los Angeles Co.	1
Pearblossom Pumping Plant, Los Angeles Co.	1
Cedar Springs Reservoir Site, San Bernardino Co.	2
Perris Dam Site, Riverside Co.	2

There is an additional seismoscope at the Badger Hills Pumping Plant.

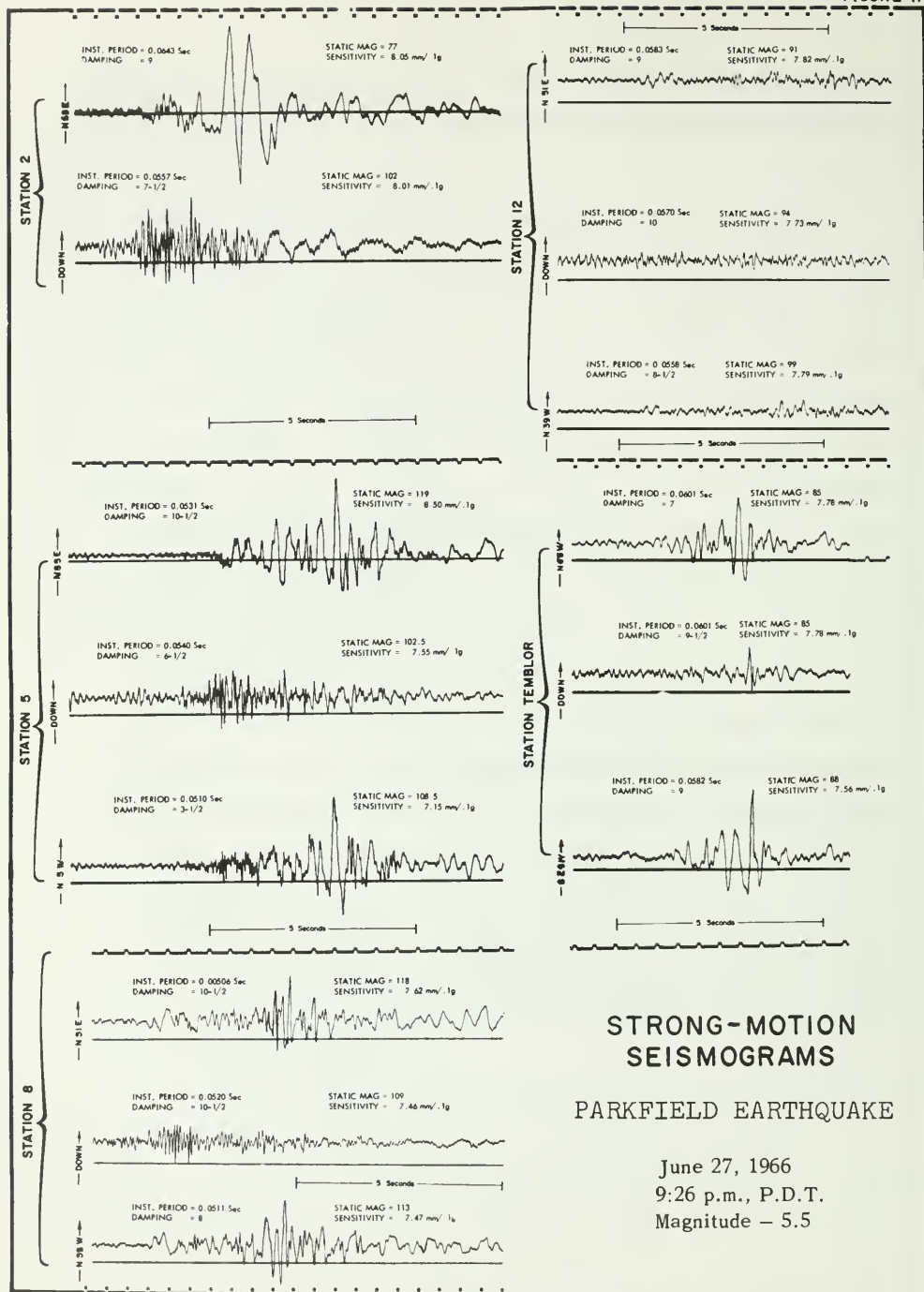
The installation of strong-motion seismographs was initiated during the 1963-64 fiscal year, when 12 instruments were installed. Thirteen more were installed in Fiscal Year 1964-65 and another six during Fiscal Year 1965-66.

Five instruments used for strong-motion recording are USC&GS standard strong-motion seismographs. Twenty-four instruments are Teledyne Model AR-240 strong-motion accelerographs.

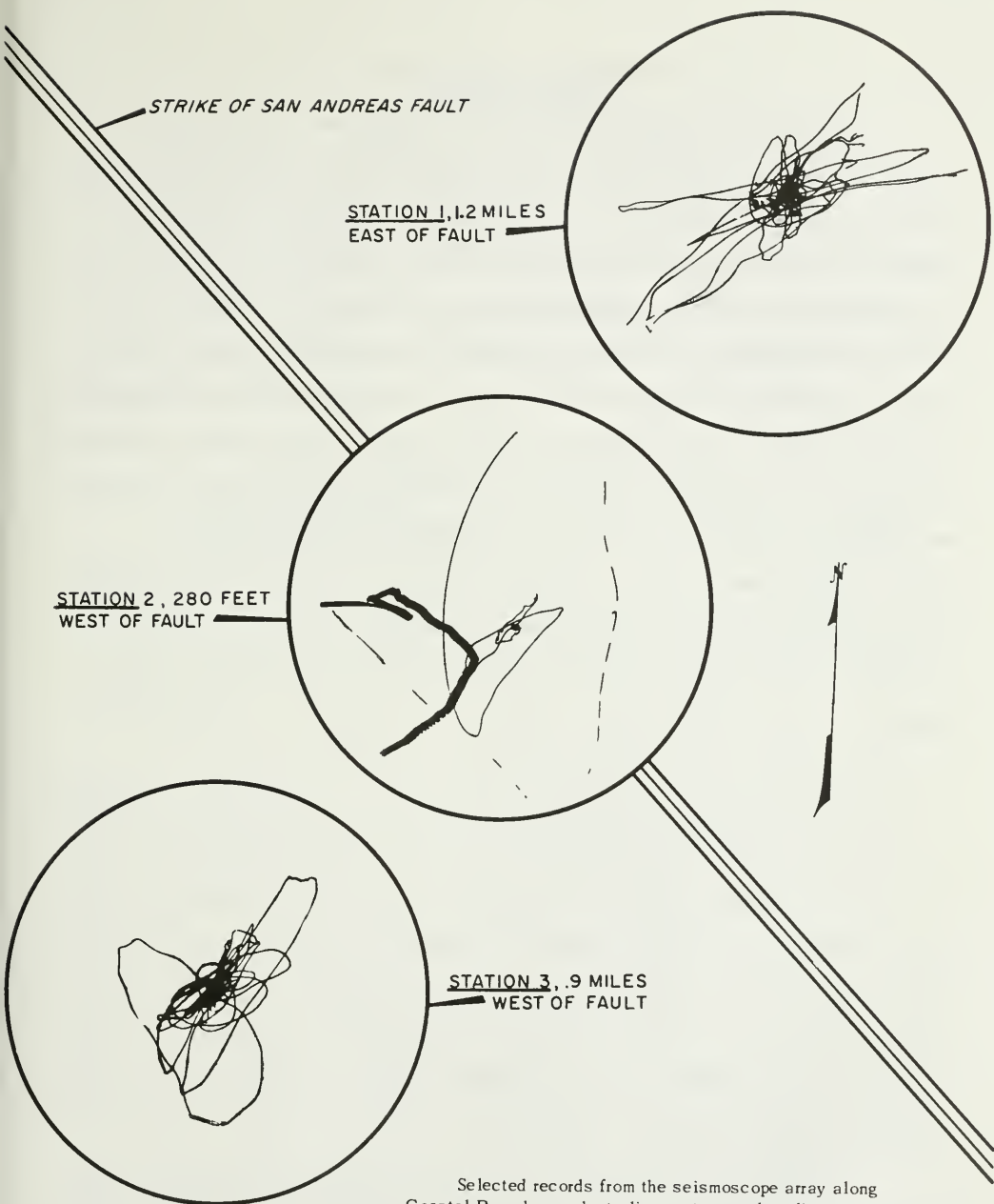
Additional strong-motion instrumentation is planned for Oroville and Castaic Dams. Each major facility will have at least one and preferably two strong-motion seismographs. The completed net will have a minimum of 70 strong-motion seismographs and about 100 seismoscopes. The Army Corps of Engineers,

the U. S. Bureau of Reclamation, and the County of Los Angeles also require that strong-motion instrumentation be placed in major structures or hydraulic facilities.

Several of the Department's strong-motion seismographs were triggered during the series of three earthquakes in the Magnitude 5 range near Parkfield, Figure 30, in late June 1966. Four of the instruments are located in a line, at right angles to the San Andreas fault near the route of the Coastal Branch of the California Aqueduct. The Coastal Branch array of seismographs is several miles south of the epicenter but adjacent to the fault in the zone of movement. Station 2, the station nearest the San Andreas fault (approximately 250 feet from the surface break) recorded accelerations of about $1/2g$, the largest ever recorded in California (Figure 17). Only the component perpendicular to the fault was operable at this station, so the total maximum ground accelerations could have been higher. The seismoscope at this station went completely off scale, something never before documented. In the process, this seismoscope recorded thick and broken lines, a somewhat unusual record (Figure 18). Damage in this relatively unpopulated area was slight. The duration of high acceleration was limited to a few pulses, a fact that reinforces the concept that damage intensity is related to earthquake factors other than maximum accelerations alone.



Strong-motion records from the Coastal Branch aqueduct array. The period, damping characteristic, static magnification and sensitivity of the recording instruments are indicated with each trace.



Selected records from the seismoscope array along Coastal Branch aqueduct alignment spaced at distances indicated from the San Andreas fault near the epicenter of the 1966 Parkfield earthquake. The needle on the seismoscope at Station 2 was jolted off the smoked glass surface, a possible cause of the thick, irregular trace.

SEISMOSCOPE RECORDS

Seiche Recorders

Seiches are resonant oscillations of contained bodies of water usually induced by ground motions, although high wind, passing pressure fronts, and ice or earth slides have also caused them. A program was initiated to determine characteristics of seiche development and the degree to which they may constitute a hazard to State Water Project facilities or endanger nearby population or property. The configurations of reservoirs and canals can be used to calculate the probable resonant modes of oscillations of the water, but the energy levels or wave amplitudes usually cannot be theoretically determined. Consequently, measurements are required to determine how susceptible reservoirs and canals will be to the development of earthquake-induced seiches.

Specifications for a seiche recorder were developed and a prototype purchased during the 1964-65 fiscal year. The instrument was installed for testing and calibration in East Bay Municipal Utility District's San Pablo reservoir. This area was chosen because of the relatively high frequency of small earthquakes.

The instrument is designed to detect and measure the height of seiches or long-period waves which are dependent on the geometry of the reservoir and to filter out shorter-period wind-induced ripples. It is a pressure recording system with hydraulic filters around a pressure detector. No significant earthquakes occurred during operation of the recorder which caused the generation of seiche. However, the sensitivity and effectiveness of the recorder were demonstrated by the recording of wind-generated seiches, with wave periods ranging from one to seven and one-half minutes.

Analysis of seiche records is still in an early developmental stage because of the limited number of recordings. The technical literature contains

many reports of damage caused by earthquake-generated seiches and also by wind-generated seiches. However, most of the reports are based solely on eyewitness accounts. A few seiches have produced instrumental records, but these were taken from tide gages and water level recorders with slow response characteristics and recording speeds. This limits their utility for analysis.

Because seiche recording and analysis are still in a developmental stage, and in the interests of economy, the seiche recorder program has been deferred as of June 30, 1967.

Special Instrumentation for Oroville Dam

Three completely new and unique instrumentation systems have been installed in Oroville Dam to monitor the dynamic responses of the dam during earthquakes. Two of these, the force-balance accelerometer and dynamic stress meter, are instruments developed for the space program and modified to meet Department needs.

The dam is in an area of relatively light seismic activity. An earthquake on December 27, 1869 caused the most severe earth vibration of record in this area and was probably the only shock which might have caused damage to modern structures at the damsite. (Historical records refer to a moderate shock in Western Nevada on that day, but the USC&GS has suggested that an independent strong shock centering near Oroville would be required to explain the significant damage to brick buildings there.) Even during mild earth tremors, however, valuable information can be obtained from the dynamic instrumentation in the embankment. Conformance of embankment behavior to design criteria can be studied. In the event of more severe activity, the data obtained will augment that obtained from conventional instrumentation also

installed in the dam and help define zones and areas of maximum stress in which inspection should be concentrated. The information from all the sensors in the dam will permit a more complete analysis of the stress-time history of an earthfill structure than has ever been possible.

Reinforced concrete instrument terminal vaults located in the downstream face of the dam enclose the monitoring equipment and recorders, which are automatically activated during a seismic event. The sensors, embedded in appropriate zones of the dam, are connected to the monitoring equipment by over 50,000 feet of direct-burying multiconductor shielded cable.

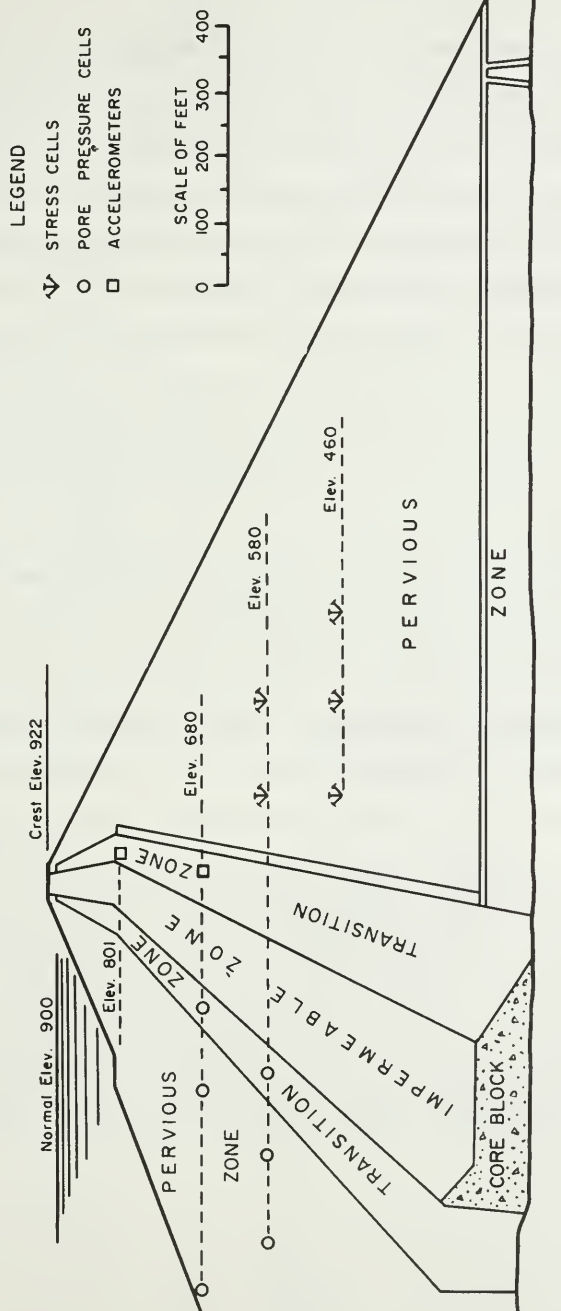
The locations of the three systems within the dam are shown in Figure 19.

The development and testing of the dynamic systems has been carried out under the guidance and according to specifications established by the Department. The dynamic stress cells and related monitoring systems were designed, fabricated, and calibrated by Aerojet General Corporation, Sacramento. The hydrodynamic pore pressure cells and related monitoring system were designed, fabricated and calibrated by Teledyne Corporation, Earth Sciences Division, Pasadena. The accelerometers and related control system were designed, fabricated and calibrated by Geo-Recon, Inc., Seattle. All systems were installed in the dam by the Oroville Dam contractor, Oro-Dam Constructors.

Stress Cells

A network of fifteen stress cells has been installed in the downstream pervious zone of the dam. This zone, free of pore pressure, will

DYNAMIC INSTRUMENTATION IN OROVILLE DAM



Three kinds of instruments will monitor dynamic responses in the Oroville Dam: (1) Stress cells are essentially hydraulic cells, each equipped with two independent, dissimilar sensors for verification of results. The data recorded during an earthquake will help define zones and areas of maximum stress. The recorder may be activated manually for determining static stresses, or triggered automatically by seismic events for monitoring dynamic stresses. (2) Pore pressure cells measure pore pressure developed in the saturated, pervious and transition zones during an earthquake. (3) Triaxial accelerometers embedded in the embankment and foundation utilize a pendulum suspended within the field of an energized coil to measure acceleration. The acceleration trace thus developed is permanently recorded on two oscillograph recorders.

furnish the greatest strength and resistance against the water load from the full reservoir.

The stress cell contains hydraulic fluid under pressure, which is monitored by electrical sensors. Initial calibration is performed in the laboratory with a high precision compression apparatus. Each stress cell is equipped with two independent and dissimilar sensors for verification of results. The primary sensor is an unbonded strain gage manufactured by Consolidated Electrodynamics Corporation. The recorder for this resistance-sensitive transducer is a Honeywell Model 1108 Visicorder on which a trace from each of the strain gage sensors is simultaneously recorded for the fifteen stress cells. This recorder may be activated manually for monitoring stress under static conditions, or triggered automatically by a seismic event exceeding a predetermined intensity.

The redundant sensor of each cell is a vibrating-wire, frequency-modulated system developed and manufactured in Germany by Maihak. The signal is modulated only by the vibration frequency and is independent of resistance of impedance variations in the circuitry. Monitoring involves the electrical matching of frequencies of a comparator wire with the sensor wire through the use of an oscilloscope. The vibrating wires can be excited automatically at preset intervals, or manually by push-button control. Each cell is monitored individually, one at a time on this system providing a static stress measurement to correlate with continuous records from the primary sensor.

The body of the stress cell is fabricated from stainless steel. It measures 30 inches in diameter by 5 inches thick and weighs approximately 1,000 pounds. The unusually large size of the cell was established to average

out stress concentrations resulting from embedment in a very coarse cobble-size aggregate in which particle sizes of 4 inches to 6 inches are common.

One of the significant features of the cell is an adjustment which permits the stress-strain response to conform to the elastic modulus of the soil in which it is to be placed. Matching the cell to the soil modulus assures that the stress across the cell is identical to that in the soil mass. This is made possible during calibration by permanently pressurizing the cell fluid against two metal spring-loaded bellows riding on the fluid pressure. A load-displacement ratio equivalent to a given elastic modulus is thereby established.

The fifteen cells are in five groups of three cells each. Each cell in a group is installed in a different plane of orientation. The horizontal cell responds to vertical stress. A second cell dips 45 degrees upstream, and a third 45 degrees downstream, to register appropriate normal stresses in the embankment and permit a determination of magnitude and direction of principal stress.

Figure 20 is a photograph of the installation of stress cells in the Oroville Dam embankment.

Pore Pressure Cells

The second of the three dynamic systems installed in the dam is similar to the first but designed to measure pressure of the pore water in the upstream pervious zones, which will be saturated by the full reservoir. Six cells, called hydrodynamic pore pressure cells, are located as shown in Figure 19. These cells are modified Carlson pore pressure cells. The standard Carlson sensor is of the unbonded strain gage type, consisting of



Fifteen stress cells, in groups of three, are located in Oroville Dam. Two of the thirty-inch cells are visible. A third is out of sight in the rear trench. Each cell is installed in a specific plane of orientation to determine the magnitude and direction of principal stresses developed during an earthquake. The stress cells incorporate a unique feature whereby the stress-strain response of the cell can be adjusted to conform to that of the soil.

Figure 20. INSTALLATION OF STRESS CELLS IN OROVILLE DAM

two coils of fine steel wire. The expansion coil and the contraction coil respond to strain, and the variation of resistance ratio of the two coils over the pressure range of the cell is calibrated. This type of sensor has the advantage of being temperature compensating. A special external casing was adapted to the standard Carlson cell to provide protection while embedded under several hundred feet of gravel and cobble overburden. The casing is vented in a way which offers a minimal impedance to transmission of fluid pressure waves to the sensor but prevents deposition of fine soil particles from obstructing it.

The monitoring system for the hydrodynamic pore pressure cells consists of a six-channel balance and calibration network. The system provides completion arms for one and two active arm bridges, as well as conventional four-arm bridge termination. Transient pressure data during a seismic event will be recorded on a direct writing recording oscillograph manufactured by Brush Instruments.

A photograph of a cell appears in Figure 21.

Accelerometers

Both the dynamic stress monitoring system and the hydrodynamic pore pressure monitoring system contain a relay network designed to sense a triggering signal generated by a new type of accelerometer manufactured by Geo-Recon, Inc. The Geo-Recon Seismic Detection and Recording System is the third of the above-mentioned dynamic systems designed for Oroville Dam. Three triaxial accelerometer packages, two embedded in the embankment and one in the foundation, are located as shown in Figure 19. The embankment accelerometers are designed for burial under overburden and hydrostatic pressures up to 500 feet.



Installation of a pore pressure cell in the upstream pervious zone of Oroville Dam to measure hydrodynamic pressures in saturated material several hundred feet below the crest. Inset shows upper part of the cell. Scale indicated by pencil.

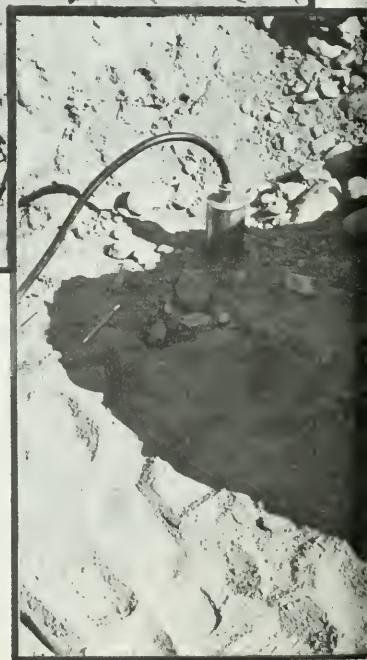


Figure 21.

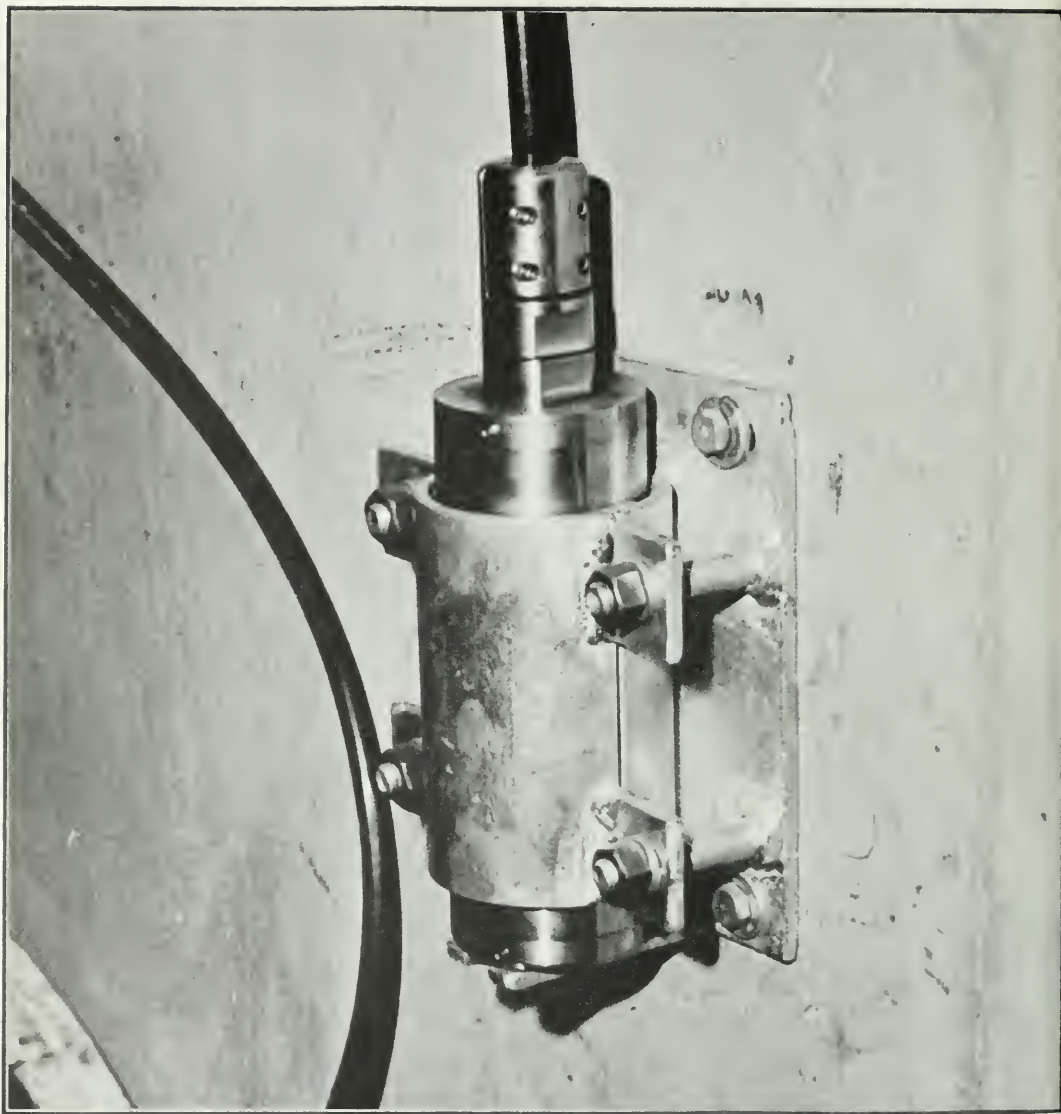
INSTALLATION OF CARLSON DYNAMIC PORE
PRESSURE CELL

The foundation accelerometer package is designed to be inserted in an NX diameter bore hole and will also withstand overburden and hydrostatic pressures up to 500 feet. A photograph of the type of accelerometer used in the dam appears in Figure 22.

The transducer adapted for the Department is a force-balance servo-accelerometer. It is a development of the U. S. Space Program for inertial guidance systems and is adaptable for operation in a remote terrestrial, as well as space, environment. The device is responsive only to accelerations and has a flat response from zero to several hundred cycles per second. This flat response characteristic is highly advantageous because earthquakes theoretically generate all frequencies. Another advantage for this device is its wide dynamic range, at least 120 db.

The transducers are powered at all times when the system is on standby. Controls for automatic operation include facilities to obtain automatic triggering from any one of the nine transducers in the system (three at each instrument, one in each axis), adjustment for the acceleration level at which automatic triggering occurs, and an adjustment for the length of time that automatic recording shall continue following each triggering cycle. The necessary nine channels for recording the acceleration traces will be provided by two oscillograph recorders.

It is contemplated that the vertical sensor in the foundation accelerometer package will be used for earthquake monitoring and will be used to trigger the recorders for all dynamic monitoring systems in the dam. Plans for the utilization, augmentation and enhancement of these dynamic systems are currently being extended. It is probable that measurements of strong accelerations will also be made at several points on the surface of Oroville Dam embankment by the installation of self-contained strong-motion detectors and recorders



One of three triaxial accelerometers being installed in Oroville Dam. Two are embedded in the embankment and one in the foundation. The device is responsive only to accelerations, and records frequencies from zero to several hundred cycles per second. It is activated by earthquake shocks and will record for a given time interval.

Figure 22. TRIAXIAL ACCELEROMETER

like the AR-240 (Teledyne, Inc.) instrument now installed in the Oroville seismograph station approximately 1 mile north of the dam. Plans are being considered for a number of detectors, to be placed on mountaintops surrounding the dam, that would turn the power on in the accelerometers by radio before the initial earthquake shock reached the dam. This early signal would ready the accelerometers for the shock, thereby reducing, or eliminating, loss of the initial acceleration records. Simultaneous tape recording of all data is also a future possibility but probably not in the early stages of operation.

Analysis of Historical Earthquake Damage

Available data on earthquake damage to hydraulic structures in California have been collated and compiled for a rapid indexing and retrieval system to provide basic data for seismic hazard appraisals and other engineering programs.

The first earthquake in California of which we have a written record was reported by a Spanish ship docked at San Diego in 1769. But it wasn't until 1800 that the first earthquake damage was reported. A detailed earthquake investigation of the 1906 San Francisco earthquake was made by the California Earthquake Commission and a comprehensive three-volume report of its work was published. Since that time, data have been collected on all large and many small earthquakes by government agencies, private companies, and individuals.

To illustrate the relative earthquake hazard in all State Water Project areas, an intensity map, Figure 23 was compiled from USC&GS intensity descriptions to show the number of times during a 50-year period that all

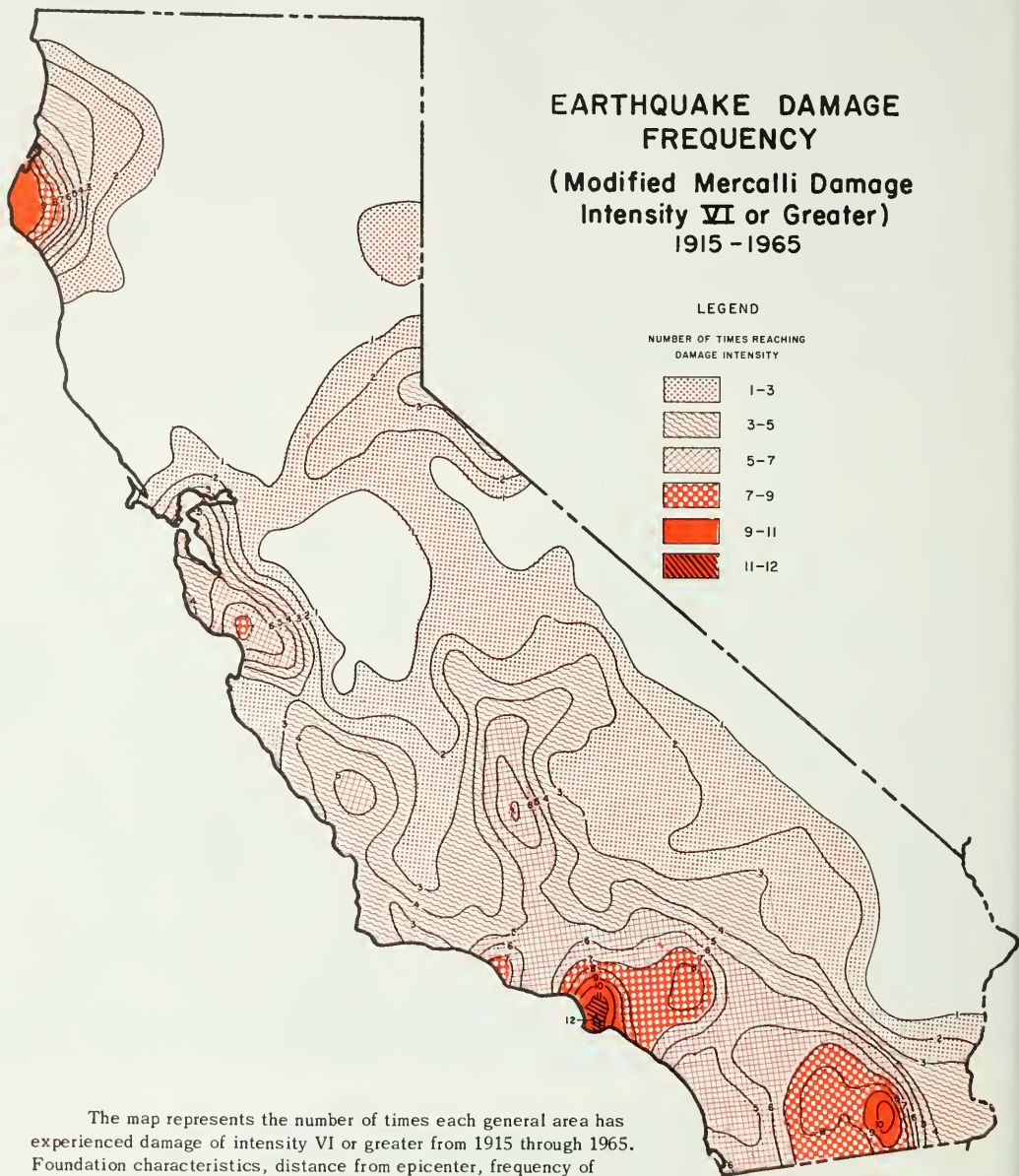
EARTHQUAKE DAMAGE FREQUENCY

(Modified Mercalli Damage
Intensity VI or Greater)
1915 - 1965

LEGEND

NUMBER OF TIMES REACHING
DAMAGE INTENSITY

	1-3
	3-5
	5-7
	7-9
	9-11
	11-12



The map represents the number of times each general area has experienced damage of intensity VI or greater from 1915 through 1965. Foundation characteristics, distance from epicenter, frequency of earthquakes, population density, and other factors influence the damage history of locality. The period of record is too short for an accurate indication of the relative susceptibility of each location to heavy damage over a long period of time.

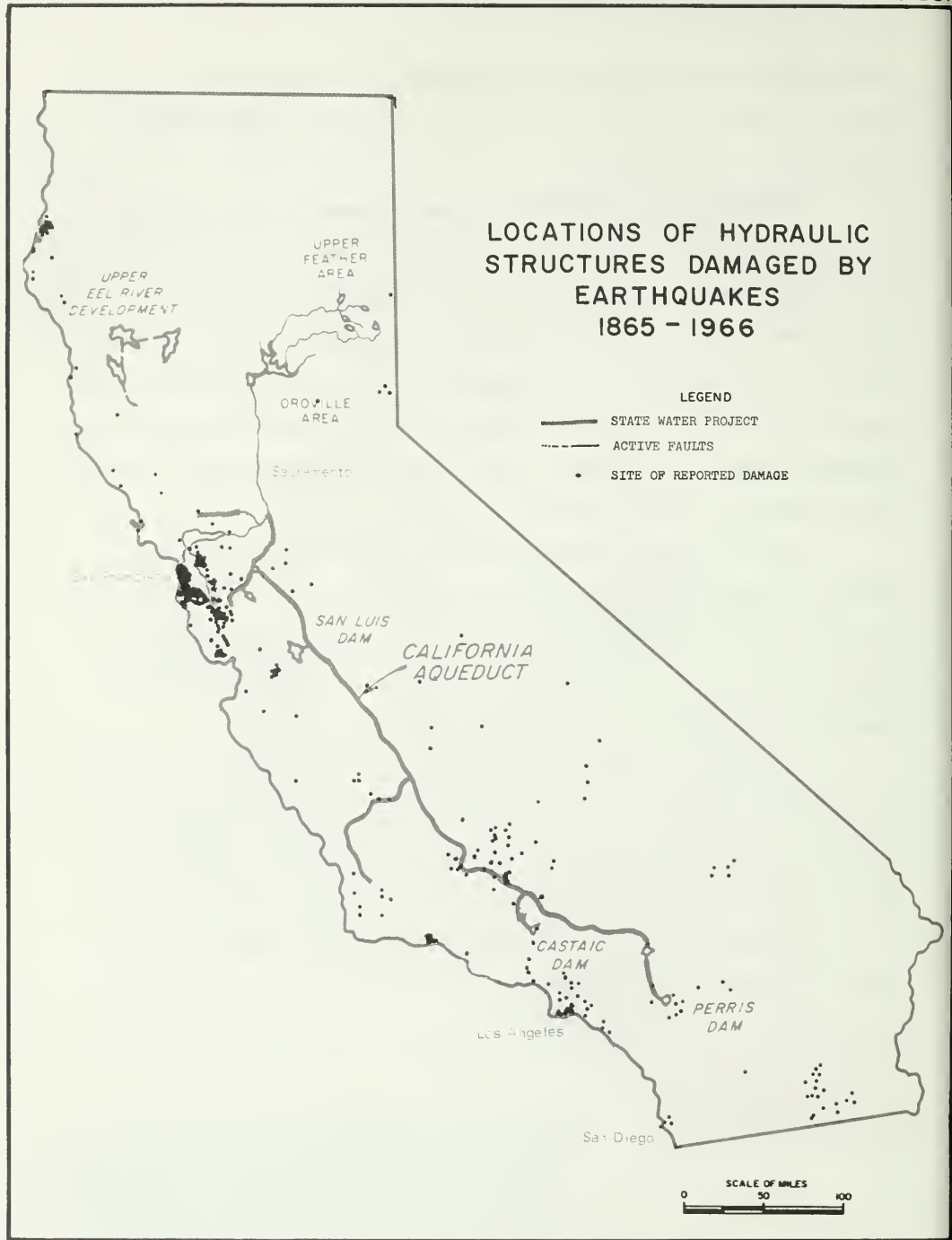
areas of California have been subjected to shaking of Intensity VI or greater (Modified Mercalli Scale). Intensity VI is the level at which structural damage generally first appears.

To provide basic data on the types of damage which may affect the State Water Project, copies of all available published and unpublished reports on earthquake damage to hydraulic structures in California are being obtained, indexed, and stored in a computer data retrieval system. We are indebted to the University of California for the compilation of data from its earthquake newspaper file. Figure 24 is a map showing locations of hydraulic structures in California damaged by earthquakes. These include dams, powerplants, pumping plants, aqueducts, water tanks, etc.

Data on earthquake damage to canals and pipelines were used in comparing alternative alignments of the California Aqueduct in Antelope Valley. Subsequently, the compilation was completed and prepared for publication in August 1964 as an office report entitled, "Earthquake Damage to Canals and Pipelines in California".

Additional data on canals and pipelines and new data on earthquake damage to other hydraulic facilities have been collected and compiled in Bulletin 116-3, "Earthquake Damage to Hydraulic Structures in California", which will soon be released. Figure 24 is based on data in that bulletin.

Earthquake damage and intensity data are being transferred to a format suitable for digital computer use.



CHAPTER IV. COLLECTION AND ANALYSIS OF TECTONIC DATA

Geodetic surveys constitute a major segment of the Data Collection and Analysis programs. This requires special instruments and procedures not generally encountered in conventional survey practice. The cooperative cost-sharing agreement with the U. S. Coast and Geodetic Survey provides the capability for extensive and very precise surveys necessary for both ground movement investigation and basic Project survey control. Personnel of the Department plan the geodetic survey activities accomplished under the cooperative agreement and engage in similar survey activities which are of exclusive interest to the Department or of a nature not subject to federal participation.

A letter of understanding setting forth the principles of cooperation in geodetic surveys and ground movement investigation was executed between the Department and the USC&GS in 1959. Initially, precise leveling for subsidence was performed in the San Joaquin Valley. Other needed work has been accomplished under the cost-sharing cooperative agreement for Geodetic Surveys and Seismological Investigations, implemented in 1963. Geodetic survey activities accomplished by the USC&GS for the Department prior to 1963 were fully reimbursed by the State. Continuing activities currently included in the DWR-USC&GS cooperative agreement are:

- (a) Monitoring of land subsidence in the Sacramento-San Joaquin Delta and San Joaquin Valley. Data are interpreted by the U. S. Geological Survey under a federal-state cooperative ground water investigation program.
- (b) First- and second-order leveling and first-order triangulation where needed for ground movement study and/or Project survey control.

- (c) Reobservation of fault movement quadrilaterals. These are special figures designed to monitor fault creep at locations where aqueduct facilities cross major faults.

Geodetic survey activities accomplished by Department

personnel include:

- (a) Precise distance measurements with a Model 2A Geodimeter* to monitor fault creep and/or strain accumulation on major faults in areas of concern to State Water Project facilities. Project Fund support for this activity was terminated as of July 1, 1967.
- (b) Precise leveling, triangulation, Geodimeter measurements and astronomic observations for investigations of ground movements at special sites. These include detection and monitoring of landslide movements in the Upper Eel River Development, monitoring of fault creep, surveys in conjunction with tiltmeter installations, etc.

The Consulting Board for Earthquake Analysis, in its report of March 1966 stated:

"Vigorous effort should be continued in geodetic surveys of ground movement. The Board is impressed with the Department of Water Resources' Geodimeter program, which shows great promise to date, and urges that it be expanded. This program has profound engineering implication as well as scientific promise. The Board recommends continuing cooperation with the USC&GS in regional leveling and triangulation related to ground movements."

The Resources Agency's Geologic Hazards Advisory Committee Report of August 1966 stated:

"At the present time, geodetic measurements of continuing ground deformation associated with fault systems in California provide the most promising method of distinguishing active from

*The Model 2A Geodimeter is an electronic-optical instrument which will give precise distance measurements using the velocity of light. The distance is obtained by determining indirectly the time interval for a light beam to travel from the device to a distant mirror and return. Knowing the velocity of light, the distance may be computed. Temperature, pressure, and humidity field data are required for correcting measurements. Under reasonably good visibility conditions, distances of 20-25 miles can be measured.

inactive faults. This is a field in which the Committee feels strongly that the State should be making a more vigorous effort. All of the recent instances of gradual slippage on faults ... slippage of considerable engineering significance ... had been or probably could have been detected by geodetic surveying means, which in turn should have stimulated detailed geological field investigations."

Geodimeter Measurements*

The Department's Geodimeter program was formulated in 1958 to measure strain and intermittent displacements on the earth's crust. The activity received the unanimous endorsement of Ralph Tudor, Chairman, and the Board of Consultants, Feather River Project Alternative Aqueduct Route Studies. The late Dr. Hugo Benioff of the California Institute of Technology, Dr. Don Tocher of the University of California at Berkeley, Rear Admiral Charles Pierce of the USC&GS, and others also recommended that the Department initiate this activity. The Department's interest was predicated on the need to determine the location and magnitude of tectonic activity along fault systems which would have a major effect on the design and operation of the State Water Project.

Little was known of the magnitude and direction of crustal movements and distortions along the San Andreas and other major fault systems in California except for a few long-term investigations by the Geodesy Division of the U. S. Coast and Geodetic Survey. Its program consisted of repeat measurements, at intervals of several years, of fault zone triangulation and traverse networks at a few specific locations along the San Andreas. There was no program for monitoring other major active faults or faulted areas of unknown activity. The full extent of the zones of distortion, a quantitative measure of movement in the vicinity of State Water Project development, the influence of earthquakes, and the variability of movement with time were unknown.

*A detailed report on the Geodimeter Program is presented in Bulletin No. 116-6, "Geodimeter Fault Movement Investigation in California."

The purposes of the Geodimeter fault monitoring program were to:

- (a) Measure horizontal movements of the earth's crust caused by strain accumulation or fault slip near the location of present and proposed hydraulic structures.
- (b) Define the areas or zones affected.
- (c) Monitor relatively short-term strain variables for early detection of increases in potential earthquake energy. Financial support for this activity was transferred as of July 1, 1967, from the Project Fund to the General Fund.

A network of lines was established along the San Andreas fault from the San Francisco Bay Area to one hundred miles east of Los Angeles. Other lines were established on the Hayward, Calaveras, Garlock, White Wolf, San Jacinto, and Big Pine faults. Line lengths were from 8 to 20 miles and generally ran diagonally across the fault zone. Wherever possible, existing monuments of the USC&GS triangulation network were used, supplemented where necessary by new permanently monumented stations. Stations were generally located on mountain peaks or topographic highs. The first measurements were made in 1959. Annual movement rates are summarized in Figure 25.

The operation of any new complex instrumentation requires an initial period of training. Innovation and refinement increased accuracy as the crew gained experience. Every conceivable practical precaution was considered in obtaining reliable measurements. Development of ancillary equipment greatly improved the measurement of meteorological variables. Some of the more significant of these were:

- (a) A thermistor device for remote temperature measurement was developed by unit personnel. In order to determine the index of refraction along the line of sight, representative air temperatures must be determined as accurately as possible. Temperatures a few feet off the ground may differ by several degrees from those at a height of 20-30 feet. This is particularly true at stations in valleys, where temperature inversions are more frequently observed, and



ANNUAL CALIFORNIA FAULT MOVEMENT
1959 - 1965

at any location on calm nights. To determine more representative end-line temperatures, thermistors are elevated on telescoping truck-mounted poles extending up to 50 feet.

- (b) Remote balloon-carried sondes were developed capable of transmitting precise temperature data from elevations of up to 2,000 feet. Drs. Pierre St. Amand, Roland vonHuene, and others of the U. S. Naval Ordnance Test Station, China Lake, aided greatly in the development of these sondes. The radio sondes are carried aloft by helium-filled kytoons (combination kite and balloon) to obtain on-line, midline temperatures. This was initiated as a standard procedure in 1963.
- (c) A more powerful light source, a mercury vapor arc lamp, was adapted for use in 1964. Significant improvements in range, quality, and quantity of measurements under adverse conditions resulted.

Some of this equipment is shown in Figures 26, 27 and 28.

The accuracy of measurements made with the electro-optical device aroused considerable discussion, particularly during the years immediately following instrument development. The experience subsequently acquired by this unit and by other users of the device, principally the USC&GS, indicates that, when due precautions are taken, consistent results accurate to one or two centimeters can be expected over line lengths up to 30 km.

Each line measurement consists of 12 individual measurements made on each of two nights. Should the results not agree within specified limits, a third night's observation is required. This reduces accidental errors and the possibility that recorded atmospheric data are not representative of the entire line. The resulting probable error of the complete set of measurements normally does not exceed a few millimeters. A sample of the computer output for a line measurement is shown in Figure 29. Least squares adjustments of closed figures confirms accuracies consistently in the order of 1-2



Model 2A Geodimeter in foreground, reflex prism unit mounted on tripod in background and midline temperature data unit at center, with radio sonde suspended from kytoon. Thermistor probe is elevated by pole on truck to a maximum of 50 feet. In practice, this Geodimeter operates only at night, measuring lines 8-20 miles long.

Figure 26. FIELD EQUIPMENT FOR GEODIMETER MEASUREMENTS

Figure 27.
GEODIMETER LIGHT REFLECTOR



Figure 28.
GEODIMETER MERCURY ARC LAMP ADJUSTMENT



GROUND-BALLOON TEMPERATURE CODE 3

05/25/67

SARGENT 1930

FREMONT PK 2 1930

LINE NO. 18

DATE	TIME	F	TEMP	REF	IND	1/4WL	SLOPE DIST	SL-S-A	DISTANCE
51867	2210	1	17.19	1.00026657		7.49281516	16609.7599	12.79901	16596.9609
51867	2219	1	17.22	1.00026653		7.49281541	16609.7557	12.79901	16596.9567
51867	2222	1	17.27	1.00026649		7.49281571	16609.7860	12.79899	16596.9870
51867	2226	1	17.31	1.00026646		7.49281597	16609.7668	12.79900	16596.9678
51867	2231	2	17.05	1.00026673		7.45567718	16609.7689	12.79900	16596.9699
51867	2239	2	16.76	1.00026701		7.45567512	16609.7818	12.79900	16596.9828
51867	2243	2	16.61	1.00026715		7.45567409	16609.7682	12.79900	16596.9692
51867	2246	2	16.53	1.00026723		7.45567350	16609.7615	12.79901	16596.9625
51867	2253	3	16.67	1.00026708		7.27456842	16609.7782	12.79900	16596.9792
51867	2303	3	17.00	1.00026676		7.27457077	16609.7702	12.79900	16596.9712
51867	2312	3	17.33	1.00026644		7.27457309	16609.7724	12.79900	16596.9734
51867	2325	3	17.50	1.00026631		7.27457402	16609.7835	12.7990	16596.9845

MEAN DISTANCE + OFF LINE CORRECTION = 16596.9721 + 0

PROBABLE ERROR
OF THE MEANSTANDARD ERROR .0018834
OVERALL MEAN 16596.9721
99 PER CENT CONFIDENCE INTERVAL .0096727 16596.9472 TO 16596.9970

This example shows twelve individual measurements, four on each of three light beam modulation frequencies. The measurements were made between stations "Sargent 1930" and "Fremont Peak 1930" near Hollister the night of May 18, 1967. The computed geodetic distance in meters for each individual frequency measurement is given in the final column. Statistical data are computed for each measurement as shown. In this instance, the probable error of the mean of the twelve measurements is approximately 2 mm in 16,597 meters (10.3 miles).

COMPUTER OUTPUT OF TWELVE GEODIMETER READINGS FOR A SINGLE LINE MEASUREMENT

cm or less. This degree of accuracy is attainable under average conditions over most of the existing lines.

Experience acquired throughout the last few years of operation pointed out certain line characteristics which contribute to or detract from the ability to accomplish satisfactory measurements. Lines in new areas of study have been selected to minimize poor observation conditions. Examples of situations to be avoided are: (1) Lines with direct exposure to oceanic winds in locations where uneven mixing of oceanic and inland atmospheres occur. (2) Lines which have an appreciable difference in elevation between the two ends. Here temperature inversions, which are difficult if not impossible to evaluate, usually occur at the low end of the line. (3) Lines in areas subject to thermal winds generated by differentials in mountain and valley floor temperatures. These winds are particularly noticeable in low mountain passes and are usually most severe after sundown, when operations normally begin. (4) Lines which graze intervening ridges or pass at low elevations through valleys where varied atmospheric conditions may exist along the light path.

All but a few of the existing lines are located so highly precise measurements are consistently obtainable. This is particularly true of the high lines in the San Bernardino and Tehachapi Mountains and the lines through the Coastal Ranges. The most difficult lines to monitor are those in the San Francisco Bay region and lower lines in the San Bernardino-Redlands area. Here, variable atmospheric conditions including smog prevail throughout much of the year.

Since the activity was initiated in 1959, approximately 350 line measurements have been made. Most lines were remeasured annually. Significant lines were remeasured more frequently.

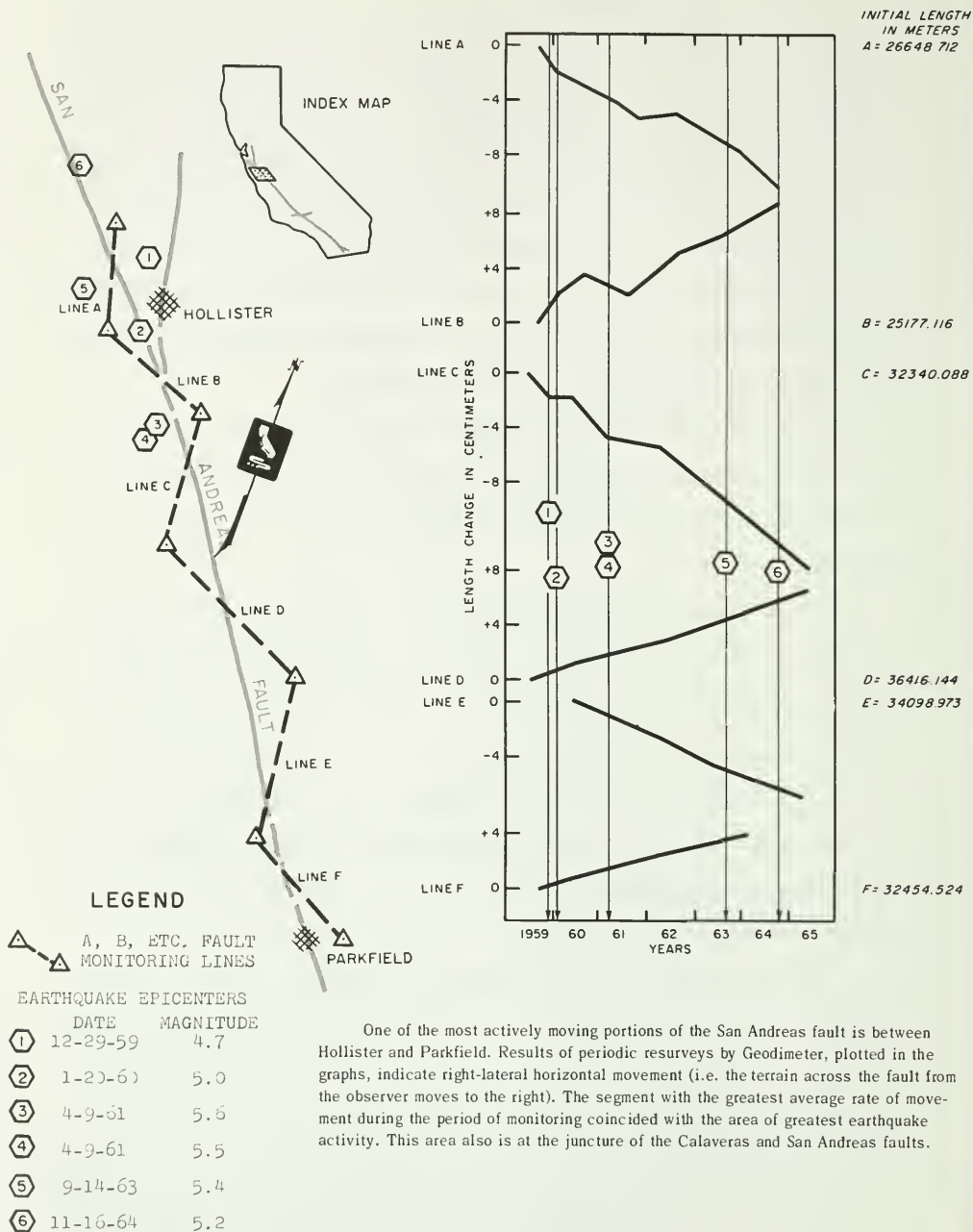
As a result, areas of movement have been defined and the rate of movement determined. An example of movement along a northern portion of the San Andreas fault is shown on Figure 30. The highest annual rate of movement measured (4.1 cm/yr.) is in the vicinity of Hollister near the confluence of the Hayward-Calaveras and San Andreas fault systems. A sample of the computer output summarizing measurement data for the two lines across the San Andreas south and west of Hollister is shown in Figure 31. Southerly from Hollister, the rate of movement gradually decreases to the vicinity of Cholame 70 miles south of Parkfield.

In the area east of Los Angeles, Figure 25, there is evidence of movement but it is not generally consistent with fault slip. The movements observed are suggestive of regional compression in a near north-south direction.

There are possible exceptions in this area where line length changes of several centimeters indicate the possibility of local adjustments on the San Andreas fault. However, the lines in this area are subject to relatively unstable atmospheric conditions.

Two lines across the Garlock fault in the vicinity of the Tehachapi Crossing have exhibited no differential movement during the period of measurement. Several new lines were established on the San Jacinto fault near the Perris Reservoir site during 1965.

In October 1965, a small network of Geodimeter lines (trilateration) was established in San Luis Obispo County in the vicinity of Cholame-Parkfield. The purpose of this figure was twofold: (a) to establish a network of interrelated lines which could be mathematically analyzed to provide further statistical evaluations of the accuracy of the field measurements, and (b) to establish additional line measurements in an area of past



CRUSTAL MOVEMENT HOLLISTER-PARKFIELD AREA

LINE NO.	DATE	OBS. D	LINE NO 17 DELTA L	GILROY TO FREMONT EXTENSION	PK DELTA T	LINE QUALITY 3 DELTA L/DELTA T	COMP. D	OBS-COMP
17	9 21 59	26648.712	0	0	0	0	26648.700	.0124
17	1 27 60	26648.690	-0.032	-1.200810E-06	.350	-0.09131	26648.690	-0.0104
17	8 21 60	26648.669	-0.011	-4.127786E-07	.567	-0.01941	26648.676	-0.0066
17	5 23 61	26648.652	-0.017	-6.379310E-07	.753	-0.02258	26648.656	-0.0039
17	9 18 61	26648.637	-0.015	-5.628806E-07	.323	-0.04643	26648.647	-0.0105
17	8 30 62	26648.643	.006	2.251522E-07	.947	.00633	26648.623	.0203
17	12 16 63	26648.606	-0.037	-1.388440E-06	1.295	-0.02857	26648.589	.0171
17	11 23 64	26648.546	-0.060	-2.251530E-06	.939	-0.06389	26648.564	-0.0183
SUM OF EXTENSIONS			SUM OF DELTA L	COMP. DL/OT	EXTENSION RATE	STANDARD DEVIATION	PROBABLE ERROR OF THE SLOPE	
-6.22921821E-06			-0.166	-0.026137	-9.80811934E-07	.01357	.00188	

LINE NO.	DATE	OBS. D	LINE NO 20 DELTA L	BROWNS TO FREMONT EXTENSION	PK DELTA T	LINE QUALITY 3 DELTA L/DELTA T	COMP. D	OBS-COMP
20	9 12 59	25177.116	0	0	0	0	25177.125	-0.0088
20	1 28 60	25177.148	.032	1.270994E-06	.378	.08470	25177.134	.0143
20	7 14 60	25177.167	.019	7.546520E-07	.460	.04131	25177.144	.0226
20	4 24 61	25177.154	-0.013	-5.163411E-07	.778	-0.01672	25177.163	-0.0087
20	9 19 61	25177.149	-0.005	-1.985928E-07	.405	-0.01234	25177.172	-0.0232
20	9 14 62	25177.193	.044	1.747613E-06	.986	.04464	25177.195	-0.0022
20	12 31 63	25177.212	.019	7.546507E-07	1.295	.01467	25177.226	-0.0136
20	11 20 64	25177.266	.054	2.144792E-06	.890	.06069	25177.246	.0196
SUM OF EXTENSIONS			SUM OF DELTA L	COMP. DL/DI	EXTENSION RATE	STANDARD DEVIATION	PROBABLE ERROR OF THE SLOPE	
5.95776809E-06			.150	.023426	9.30458006E-07	.01571	.00215	

These lines cross the San Andreas fault near Hollister. The date of measurement and observed distance in meters are tabulated in Columns 2 and 3. Note that the line "Gilroy to Fremont Peak" has shortened approximately 17 cm during the same period that "Browns to Fremont Peak" lengthened 15 cm. Various statistical data are computed for each line as shown. (Line 17 here is Line A in Figure 30 and Line 20 is Line B in Figure 30.)

COMPUTER OUTPUT SUMMARIZING FIVE YEARS OF MEASUREMENT OF TWO LINES

earthquake activity where changes in the strain pattern might be expected. Initial measurements of all lines in this figure, a pentagon with all diagonals intervisible, were completed in October 1965.

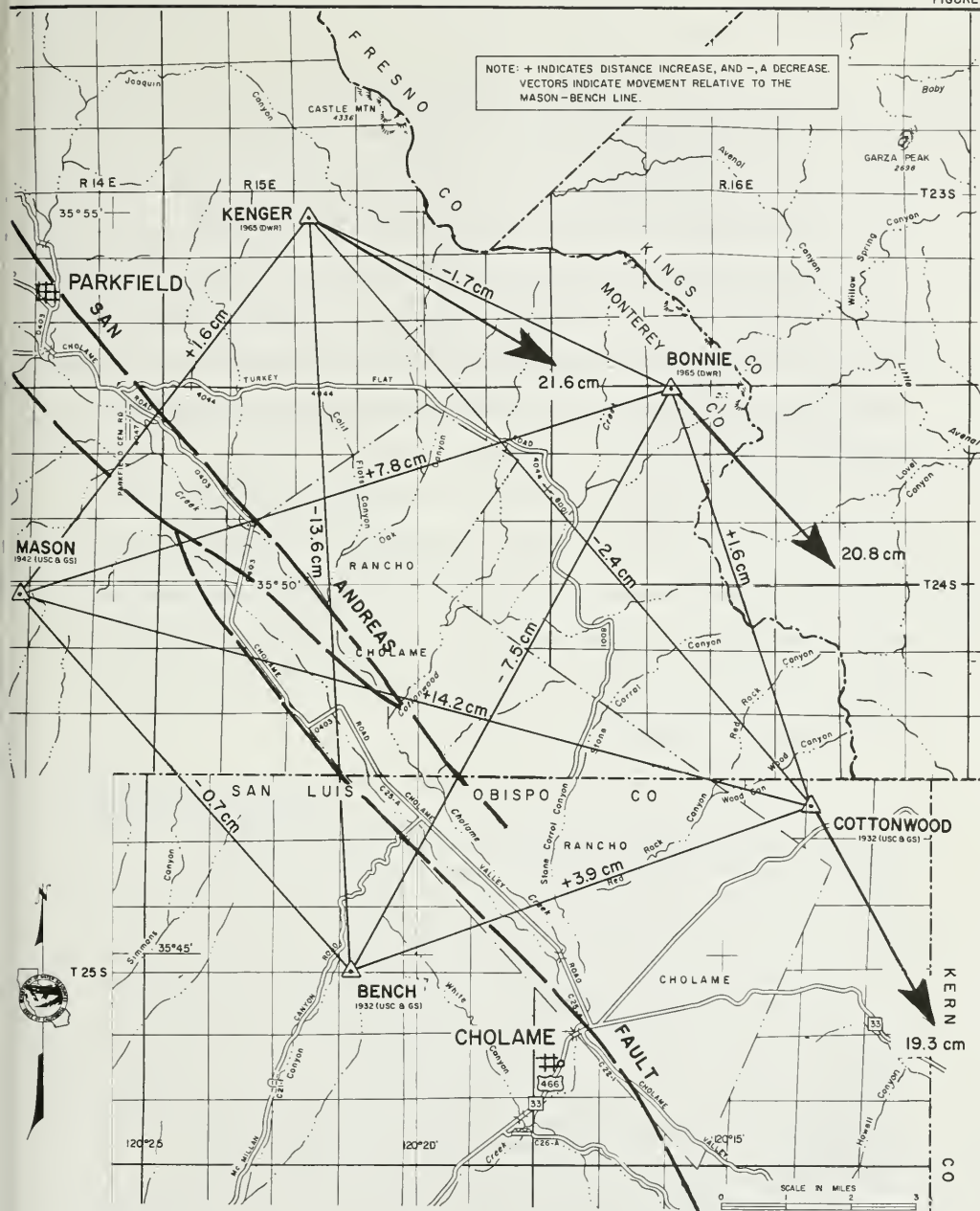
In June 1966, three moderate earthquakes occurred in the vicinity of Cholame and Parkfield. Associated with them was an initial four-inch displacement at the surface trace of the fault, an unusual occurrence for an event of Magnitude 5.7. The pentagon figure and the old lines in this area were remeasured immediately following the earthquakes.

The results of the resurvey are shown in Figure 32. Right-lateral movement of 7-8 inches had occurred. The movement appears to have been restricted to approximately a 30-mile segment of the fault centered about midway between Cholame and Parkfield. However, measurements a year after the earthquake indicate that increased movement has since progressed north of this zone. A few miles south of Cholame, where the Coastal Branch Aqueduct of the State Water Project will cross the San Andreas, results of surveys at the fault trace indicated movement of less than 0.10 foot.

Three lines across the White Wolf fault southerly of Bakersfield have been monitored with the Geodimeter. Repeat measurements indicate slight left-lateral movement in this seismically active area.

New Developments

Considerable research has been devoted to the development of an indirect means of determining the index of refraction along the measured path. The determination of this index constitutes the only practical limitation to increasing precision of distance measurements by the electro-optical method by about two orders of magnitude (100 times). The development of monochromatic light sources (lasers) during recent years may provide the solution to this problem.



CRUSTAL MOVEMENT RESURVEY-PARKFIELD EARTHQUAKE

North American Aviation Corporation, one of several interested in the problem, has developed and field tested a dual-frequency laser system. This system, known as GLASS (Geodetic Laser Survey System) operates on the basis of the difference in speed between two monochromatic light beams, each of a different wave length, propagating over an identical path. Evaluation of this dispersion makes it possible to correct for the atmospheric distortion along the light path. This system could result in consistent accuracy within a few millimeters over any line without regard to the intervening atmospheric conditions.

In April 1966, the GLASS system was field tested at Strawberry Peak in the San Bernardino Mountains. Measurements were made over one of the lines periodically remeasured in the Department's fault monitoring network. Measurements with the Department's Geodimeter were made simultaneously with the dual-frequency laser measurements. The results of these tests were encouraging and development is proceeding.

Another aspect of the optical measurement process is the measurement range capability. In California, haze and smog, which have become more and more common in areas which a few years ago were free of this condition, present an ever-increasing difficulty in obtaining measurements.

With the adoption of the mercury vapor arc lamp, measurements can be made on the many occasions when the standard tungsten light source is not adequate. A laser light source, operated toward the red end of the spectrum, would further increase the ability to penetrate these marginal atmospheric conditions and would also permit measurement over longer lines.

U. S. Coast and Geodetic Survey experiments with a laser light source, in 1965, resulted in daylight measurements of up to ten miles in moderate haze with no loss of accuracy. The results led to the permanent

modification of a Geodimeter in 1966. Daylight tests and successful measurements in daylight with components during an experiment indicate a range capability with the laser exceeding 15 miles in average hazy weather conditions. During field testing, the laser light source penetrated haze and marginal weather conditions with at least 50 percent more light return than was possible with a mercury arc lamp.

A similar instrument, the Geodolite, is in final stages of development by Spectra-Physics Corporation of California. This laser device is reported to be able to measure 20 miles in daylight and 50 miles at night.

The practical application of lasers to precise distance measurement is forthcoming. Hopefully an operational package such as the dual-frequency laser system will be developed to eliminate the problems associated with the determination of the index of refraction. In any event, the use of lasers as the future light source for precise distance measurement appears certain.

Earthquake Prediction

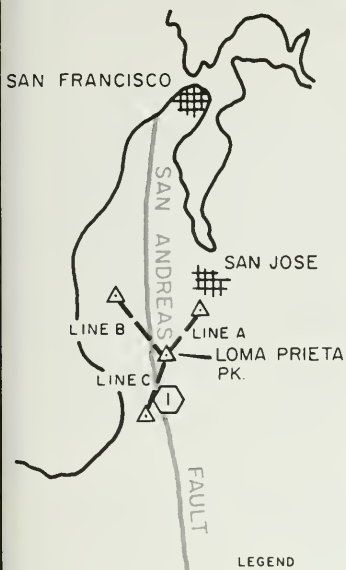
During the past few years several earthquakes in the range M 4-5 have occurred in the vicinity of the Geodimeter fault monitoring network. Some of these events were preceded by anomalously changed distances between stations near the quake-producing fault zone. The observed irregularities are relatively large and probably are not attributable to normal accuracy limitations. Some of these irregularities have been confirmed by repeat measurements of the same line and/or adjacent lines. This fact plus the coincidence of these anomalies with earthquake activity lead to the conclusion that an earthquake precursor may be observable.

The Department measures lines of the fault monitoring network on an average of once a year. The precursors have been observed two to

eighteen months prior to earthquakes. In some areas, several earthquakes of M 4 occur annually. Consequently, not all possible precursors are likely to have been observed.

An example of a pre-earthquake anomaly is shown in Figure 33. Three lines radiate from Loma Prieta, one of the higher points in the Santa Cruz Mountains approximately 15 miles south of San Jose. Lines B and C are located diagonally across the San Andreas fault. Repeated measurements of these three lines prior to 1964 confirm that little or no movement was occurring on Lines A and B, although right-lateral fault creep and/or strain accumulation was being measured on Line C. Large right-lateral movement was concurrently taking place about 10 km. southeast along the San Andreas. The fact that a significant difference in movement rate is occurring in a limited segment of the fault zone implies stress accumulation and a potential earthquake situation. In the summer of 1964 repeat measurements were made of these three lines. Note the anomalies which occurred on all three line measurements. The anomalies of Lines A and C are too large to be ascribed to measurement error. The indication of deviation in Line B is probably also significant. Note that the changes in the lines crossing the San Andreas confirm each other. This apparent left-lateral movement probably results from right-lateral movement of the small fault east of the San Andreas. (Probably an extension of the known active Sargent fault in the Hollister area.)

On November 15, 1964, an earthquake of Magnitude 5.2 occurred on the San Andreas fault near the community of Corralitos, very near Line C. Measurements of Lines B and C completed after the earthquake indicate essentially a return to the pre-earthquake situation, with some indication of right lateral motion during the following shock.



LEGEND

- PROBABLE ERROR INDICATED BY DIAMETER OF OUTER CIRCLES
- ⬡ CORRALITOS EARTHQUAKE, NOVEMBER 15, 1964, MAGNITUDE 5.2
- ⬡ EP CENTER OF CORRALITOS EARTHQUAKE

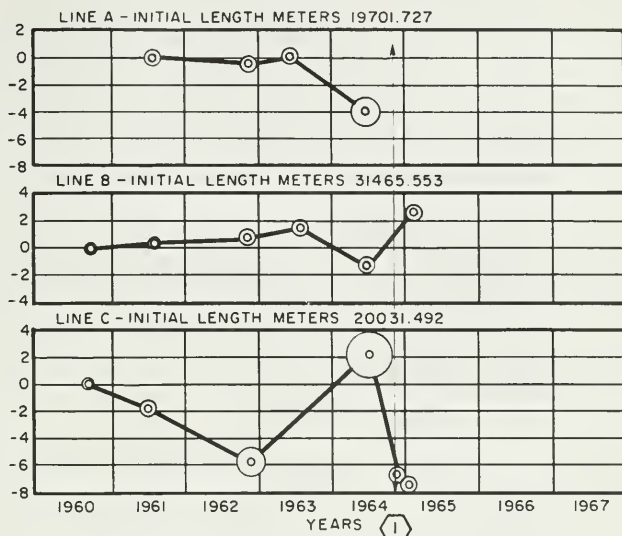


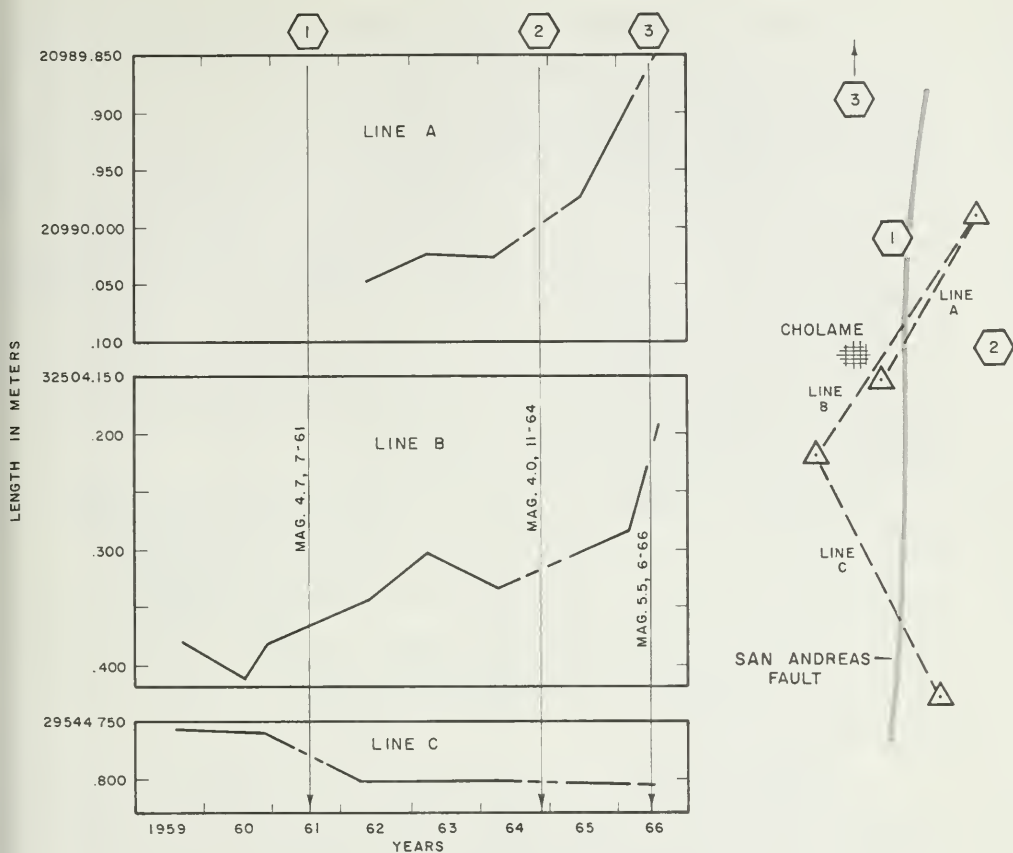
Figure 33. CRUSTAL MOVEMENT AND CORRALITOS EARTHQUAKE

These measurements are considered particularly significant because of the confirmation of anomalous activity on adjacent lines.

The relationship between fault movement and earthquake activity in the vicinity of Cholame in San Luis Obispo County is also noteworthy. (The results of these measurements immediately before and after the Parkfield-Cholame sequence of June 27-29, 1966, were previously discussed under "Geodimeter measurements".) Two lines crossing the San Andreas in a NE-SW direction near Cholame confirm right-lateral movement at a rate of nearly 3 cm per year. Some minor earthquakes ($M 4-4.5$) which occurred during the 6-7 year measurement period appear to be associated with deviations from the normal movement rate as shown on Figure 34.

Measurements of the lines near Parkfield exhibited local anomalies thought to be associated with the Parkfield earthquake. The two lines nearest the epicenter indicated mean annual changes of 1 and 3 cm/yr. This contrasted with the adjacent lines to the NW and SE, which indicates about 2 cm/yr. A local discontinuity in the strain rate was present in a limited area, a condition to be eventually relieved by an earthquake. Awareness of this condition led to the establishment of the Parkfield-Cholame pentagon in the Department's fault monitoring network, October 1965. An earthquake of about Magnitude 5+ occurred June 1966 as discussed previously.

Consistent movement on the San Andreas fault occurs on the segment of the fault between Hollister and Cholame. The highest rate of movement occurs just south of Hollister (approximately 4 cm per year), decreasing gradually to zero south of Cholame. There is also considerably less movement on the San Andreas fault north of Hollister. In each case, the boundary areas of differential movement (Hollister and Cholame) are subject to relatively frequent felt earthquakes. In the Hollister area, where the movement



Relation of San Andreas crustal movement to earthquakes near Cholame. Numbered hexagons indicate earthquake epicenters (on map) and time (in graph) during the period of monitoring across the fault. Length changes of Geodimeter Lines A, B, and C indicate the following:

1. A general, but uneven, right-lateral movement from 1959 to early 1966. Rates of change were about 2 cm/year for line B and 1 cm/year for line C. The greater movement near line B appears to be related to its proximity to the earthquake epicenters.
2. A slight reversal or at least a pause in movement occurred prior to the earthquake of 11/64. More frequent measurements would greatly elucidate the significance of this and other examples of "erratic" behavior prior to earthquakes.
3. Some nonuniformity in the rate of movement is noted on most lines before and after earthquakes. Such deviations from a uniform rate of movement are barely perceptible for some earthquakes, but pronounced deviations may be noted for others such as the earthquakes of June 1966 near Parkfield.

CRUSTAL MOVEMENT AND EARTHQUAKES CHOLAME AREA

is distributed among other local faults(eg. Sargent, Hayward, and Calaveras), frequent small earthquakes (Magnitude 3-4) are associated with the continued strain change. In the Cholame area, where the differential movement has not been accounted for, the historical trend seems to be larger (Magnitude 5-6), less frequent earthquakes. It may be that the complete lack of detectable movement to the south between Cholame and San Bernardino indicates a potential for a very large earthquake.

Relatively large fluctuations in line length have been measured prior to some earthquakes of Magnitude $4-5\frac{1}{2}$. Whether they precede earthquakes of greater magnitude remains to be proven.

Evidence of these anomalies and the opportunities to gather additional substantiating evidence is limited by the relatively infrequent remeasurement of some lines. In addition the orientations of surficial distortions, which may not always appear, may differ for particular earthquakes and not occur in a manner detectable by the configuration of existing Geodimeter lines.

In order to firm up these theories, it would be necessary to more frequently monitor lines exhibiting these characteristics and other lines in particularly seismic areas. Wherever possible, closed figures which afford an opportunity for error analysis and least squares adjustment should be measured rather than the random lines of the existing network.

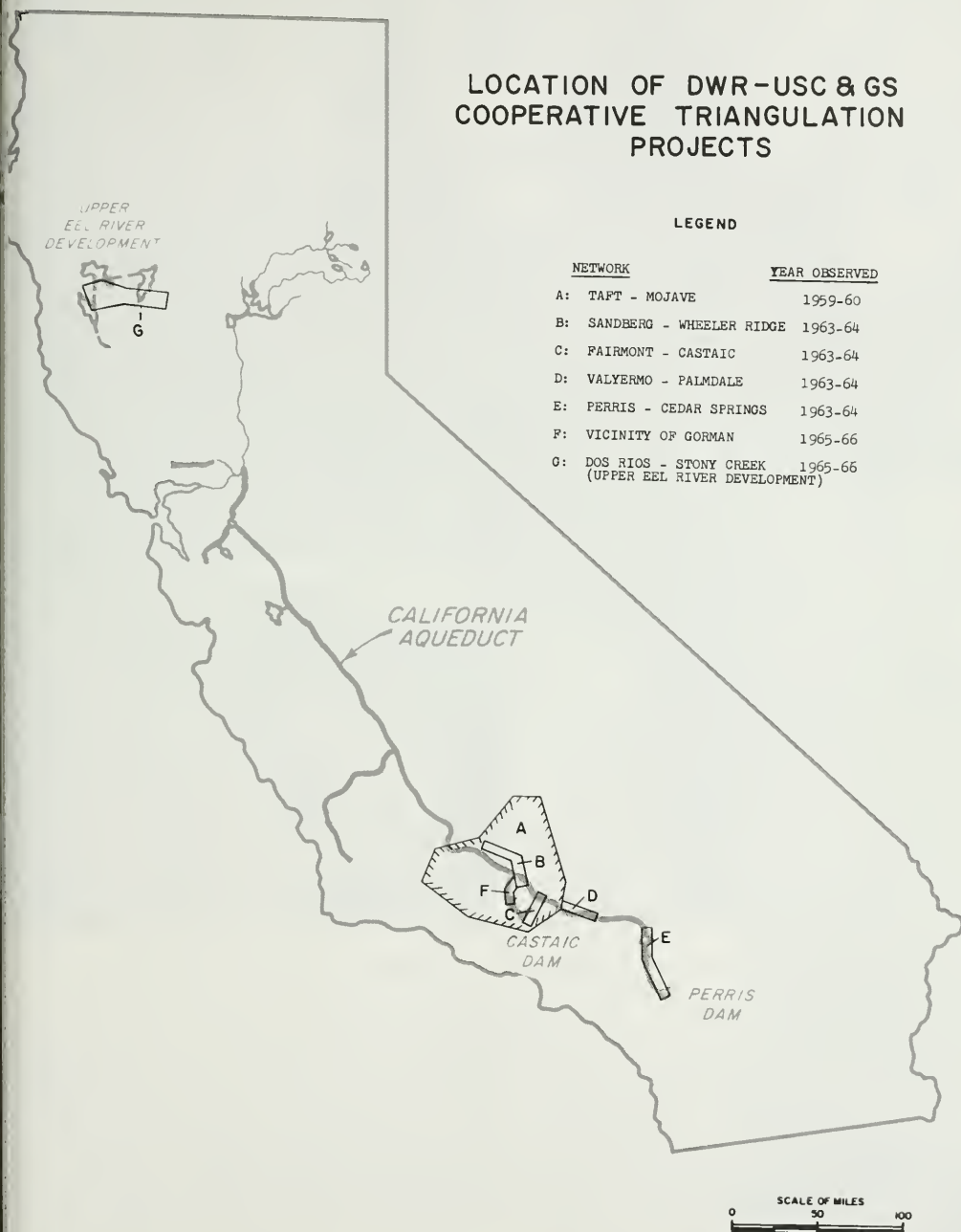
Fault Zone Triangulation

Arcs of first-order triangulation have been established along sections of the State Water Project facilities which parallel or span major fault zones. These arcs, shown in Figure 35, provide primary horizontal control for design and construction surveys and a basis by which long-term differential

LOCATION OF DWR-USC & GS COOPERATIVE TRIANGULATION PROJECTS

LEGEND

NETWORK	YEAR OBSERVED
A: TAFT - MOJAVE	1959-60
B: SANDBERG - WHEELER RIDGE	1963-64
C: FAIRMONT - CASTAIC	1963-64
D: VALYERMO - PALMDALE	1963-64
E: PERRIS - CEDAR SPRINGS	1963-64
F: VICINITY OF GORMAN	1965-66
G: DOS RIOS - STONY CREEK (UPPER EEL RIVER DEVELOPMENT)	1965-66



horizontal ground movements may be detected and measured. Segments of these arcs can be reobserved periodically and after strong earthquakes to determine the magnitude and areal extent of movement. Equipment used in performing these surveys is shown in Figures 36-39. The equipment includes a theodolite, instrument stands and a triangulation tower.

During Fiscal Year 1963-64, four arcs of first-order, Class II triangulation were established along the California Aqueduct in Southern California. A typical example of one of these arcs, "Sandberg to Wheeler Ridge", is shown in Figure 40. These projects were part of the DWR-USC&GS cooperative agreement for 1963-64, and were funded on an equal cost-sharing basis. All field and office work was performed by the USC&GS following mutual determination of routing and station locations. Geographic positions, California plane coordinates, and station descriptions have been provided.

During Fiscal Year 1965-66, two additional arcs of triangulation were observed under the cooperative agreement. In February and March of 1966, the Department and the USC&GS cooperated in the second reobservation of a USC&GS fault movement network near Gorman in Los Angeles County. This arc, which spans the San Andreas fault just southeast of the junction with the Garlock fault, was established and first observed in 1938. The second observation was completed in 1949. This network is of particular interest because it parallels the West Branch Aqueduct for approximately eight miles where this facility crosses the San Andreas fault. Analysis of data is currently in process by the USC&GS. This network is shown in Figure 41.

In the Upper Eel River Development a first-order arc was established in Mendocino and Glenn Counties. This arc extends from the vicinity of Dos Rios damsite on the Middle Fork of the Eel River easterly across the Coast Range to the Sacramento Valley. This arc spans proposed reservoir sites on

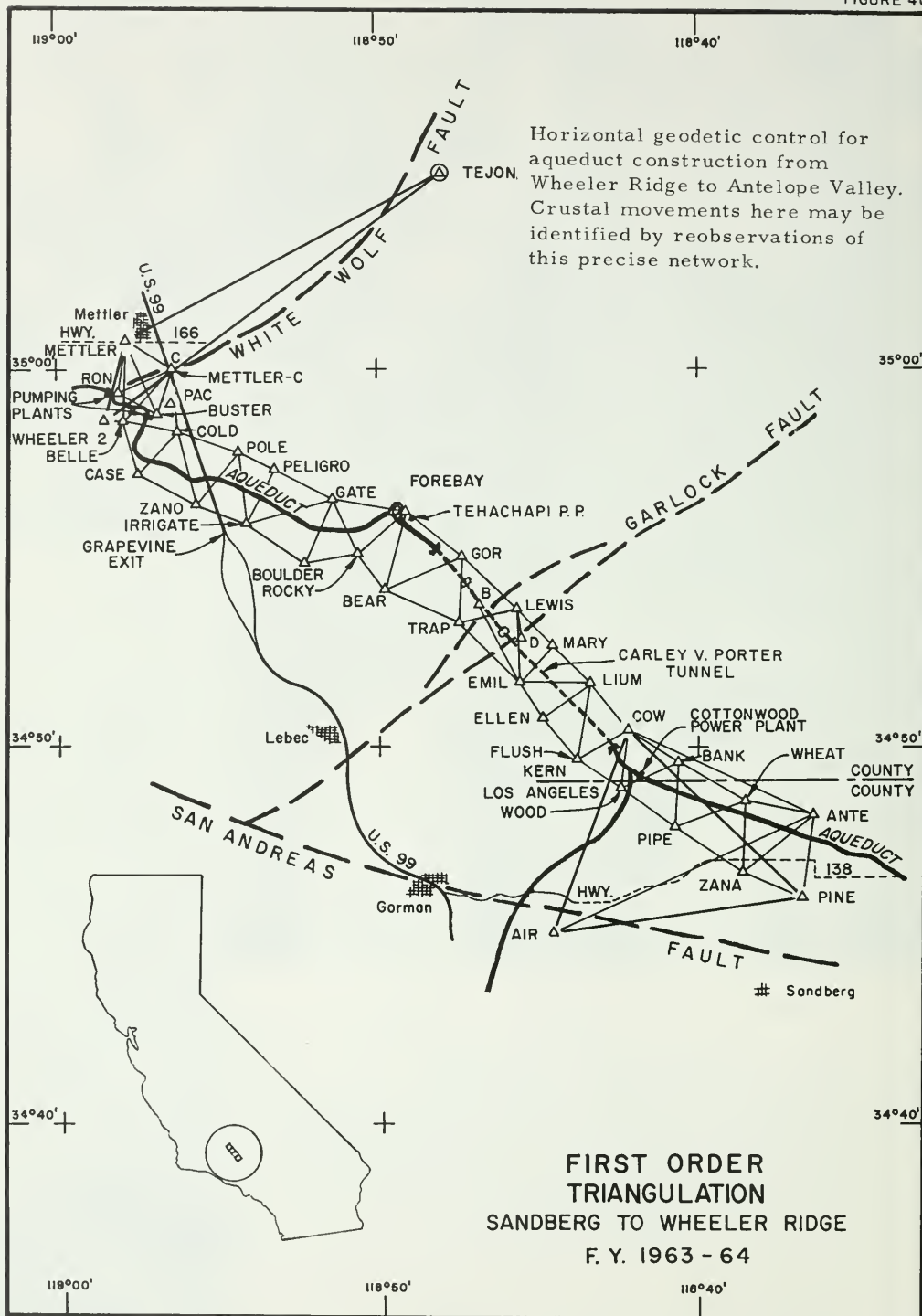


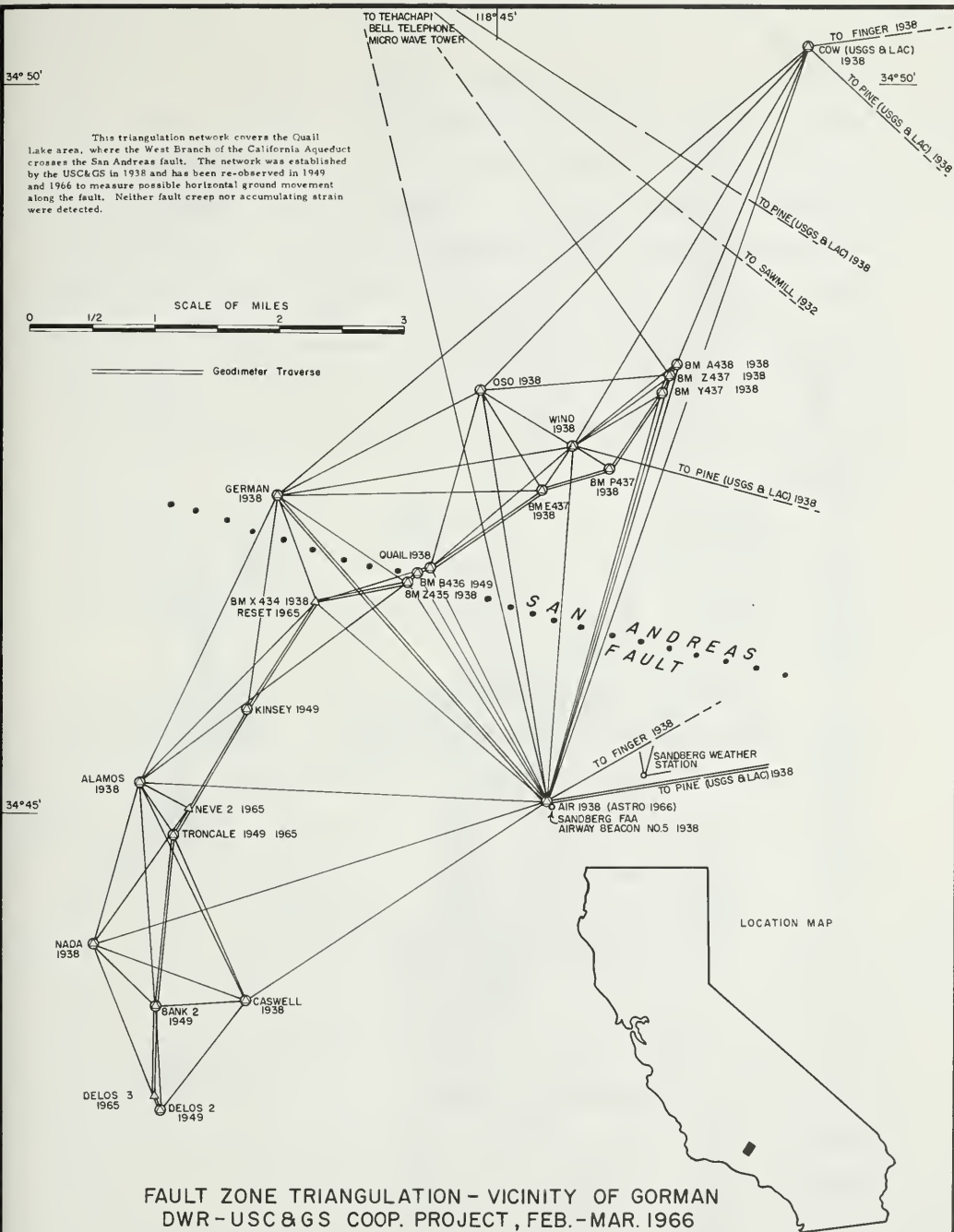
Figure 36 (upper left): The Model T-3 Theodolite

Figure 37 (lower left): Observation Tent and Instrument Stand

Figure 38 (upper right): Lightkeeper at Triangulation Station

Figure 39 (lower right): Bilby Steel Tower

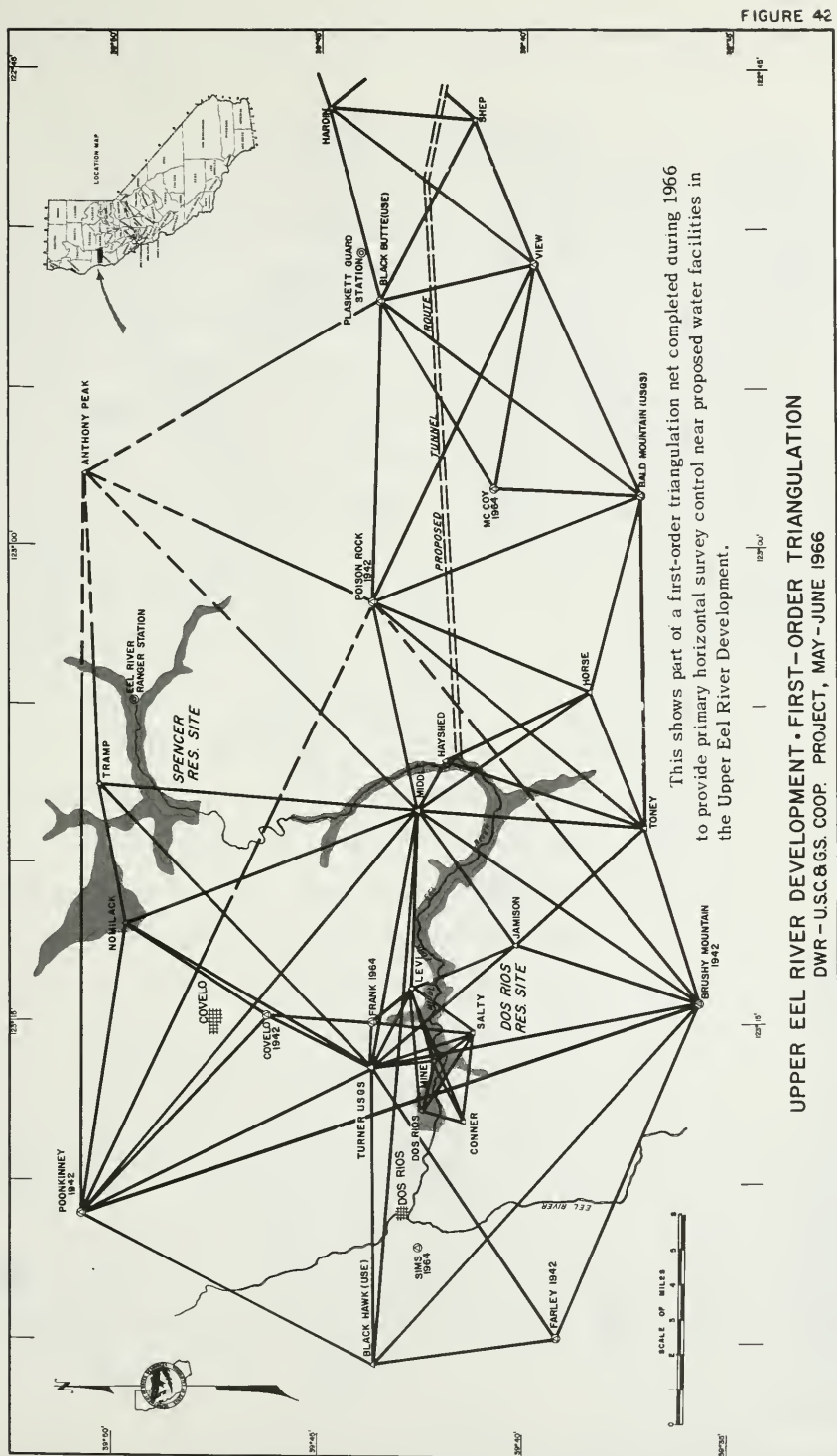




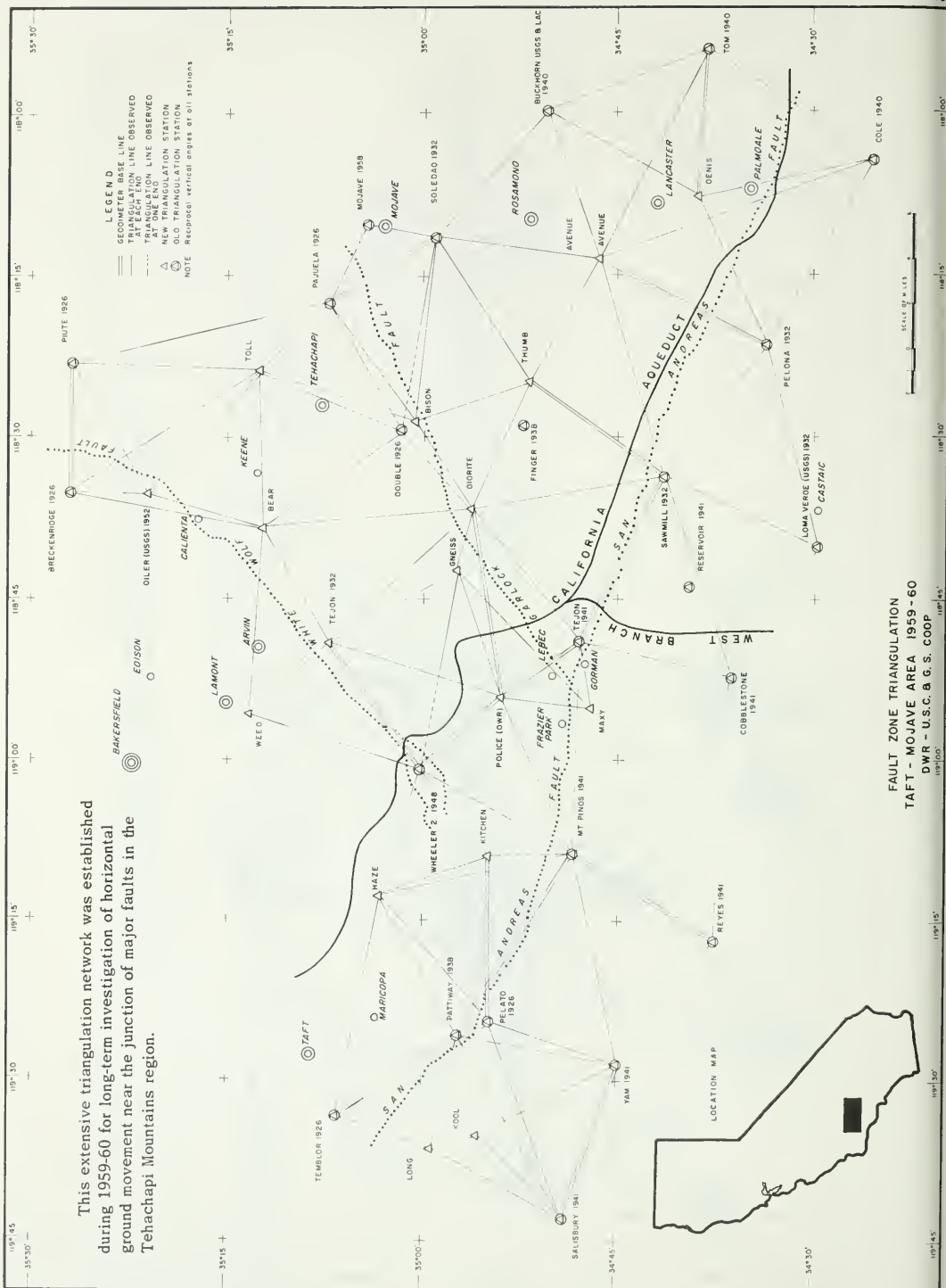
the Middle Fork Eel and ties these facilities to the proposed Glenn Reservoir Complex. Completion of this arc provides primary horizontal control for all subsequent survey activities in this region. As in the case of the Southern California arcs, reobservation of this network at some future date could yield valuable data regarding ground movements in this region. This arc crosses several fault zones in the vicinity of Round Valley, the Black Butte fault which bisects the proposed Grindstone Tunnel alignment, and the faults associated with the Stony Creek area. A sketch of the westerly portion of this network, the portion covering the Eel River Reservoir areas, is shown on Figure 42.

Concurrent with the USC&GS observation of this arc in June-July 1966, Department personnel measured several lines within the arc with the Model 2A Geodimeter. These have been incorporated into the USC&GS adjustment of this triangulation.

In recognition of the particular engineering problem involved in transporting water across the Tehachapi Mountains, a cooperative triangulation project (see Figure 43) was devised in 1959 to determine the crustal strain and fault movements in the complex area where the San Andreas, Garlock, White Wolf, Big Pine, and San Gabriel faults converge. This cooperative project with the Coast and Geodetic Survey was designed to yield upon repetition both magnitude and direction of strain and/or movement along each fault. Since completion of this network in 1959-60, many of the initial Geodimeter base line measurements, which constitute the framework for this net, have been periodically remeasured by the Department. Reobservation of this network by the U. S. Coast and Geodetic Survey is scheduled during Fiscal Year 1967-68.



UPPER EEL RIVER DEVELOPMENT • FIRST-ORDER TRIANGULATION
DWR - U.S.C.&G.S. COOP. PROJECT, MAY - JUNE 1966



Fault Movement Quadrilaterals

During Fiscal Year 1963-64, the Department began monitoring horizontal and vertical ground movements which might be occurring in the immediate vicinity of Aqueduct facilities where they cross known active fault zones. Distance measurements with the Model 2A Geodimeter over lines 8 to 20 miles in length and with stations located up to several miles away from a fault do not differentiate between movement caused by fault creep and regional strain accumulation. Highly precise geodetic measurements of short (150-500 meter) lines in a quadrilateral network directly across a fault zone will detect fault creep. The small size of the net precludes detecting strain. The strain-creep relationship can be evaluated by correlating the results of the quadrilateral and Geodimeter measurements. Knowledge of this relationship is essential to quantitatively evaluate the rate of strain accumulation.

The USC&GS agreed to cooperate in this activity as a part of its own continuing investigation of ground movement in California, and accordingly, this activity became a part of the continuing Federal-State Cooperative Agreement for Geodetic Surveys and Seismological Investigation.

Small highly precise triangulation figures were selected in consultation with the USC&GS, as the best means of detecting minute differential movements at specific areas of interest. These figures are similar to one which is monitored by the USC&GS at the Taylor Winery on the San Andreas fault south of Hollister. The surveys at the winery, repeated periodically since 1957, have successfully measured creep along the fault.

A figure of this type with slight modification was adopted for the Department's fault movement studies. This type of triangulation figure has subsequently been referred to as a "Hollister type" figure, or "fault

movement quadrilateral". Typical examples of these figures are shown in Figure 44. Locations for quadrilaterals were selected by a Department geologist working with a USC&GS geodetic field party.

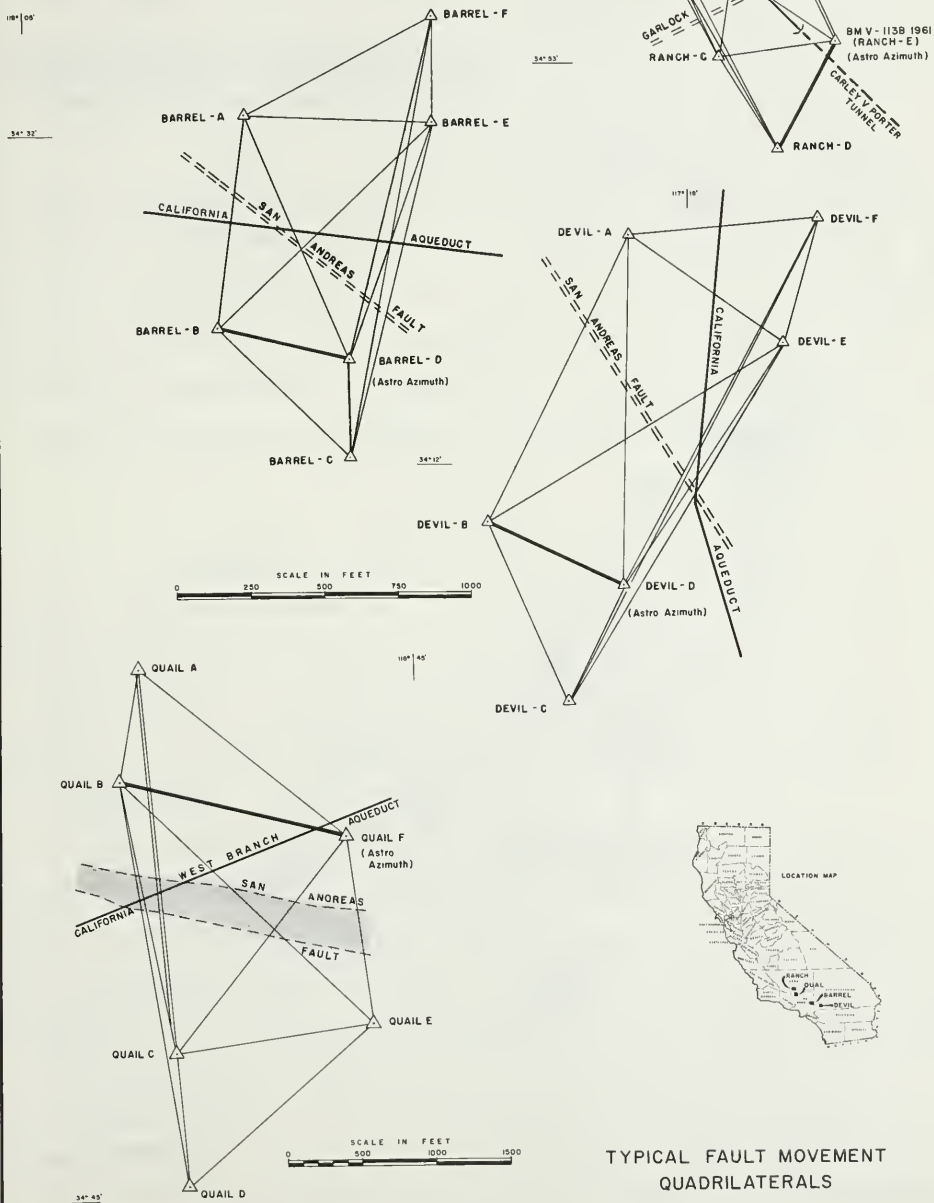
In order to detect and monitor movements on the order of a few millimeters, special surveying techniques are required. In general, first-order equipment and procedures are employed. During the past three years, however, numerous refinements have been made to observation procedures to further reduce both human and instrumental errors.

In each quadrilateral a taped base line approximately 300 meters in length is laid out parallel to the fault zone. An astronomic azimuth is observed on this base line and to a second ground station as a check. All horizontal angles are observed (on two different nights) and precise levels are run to all monuments. Monuments, when not set in bedrock, are 14-inch diameter concrete posts set five feet into the ground.

Seventeen fault movement quadrilateral networks were established and initial observations completed during Fiscal Year 1963-64. In the spring of 1965, the first reobservation of all 17 figures was completed. In addition, sites were selected and initial observations completed for four new quadrilaterals near aqueduct facilities in the San Francisco Bay area. Locations are shown on Figure 45.

Comparison of the original 1964 measurements with those of 1965 revealed some random divergence of measurements at several sites. The magnitude of the observed differences was of an order that made it impossible to specify whether these differences were observational or an indication of movement. A total of ten networks was subsequently selected for reobservation during the spring of 1966. Seven of these sites (Devil, Pear, Barrel, Palm, Ranch, Tejon, and Mettler) are located on the San Andreas, Garlock,

Fault movement quadrilaterals provide closed-figure geodetic control at aqueduct-fault crossings. As the scale indicates, these are small networks. These monitor fault creep at aqueduct crossings in contrast to the much larger triangulation and Geodimeter networks which detect both creep and strain combined.



TYPICAL FAULT MOVEMENT
QUADRILATERALS



and White Wolf faults in Southern California. These networks were observed during March-April 1966. The results of the third survey at these sites did not confirm any movement trend. The Union, Veras, and Green sites in the Bay area were also reobserved during July-August 1966. The resurvey at the Union site on the Hayward fault indicated right-lateral movement of approximately 1 cm. Surveys at Veras and Green did not confirm any movement trend.

Each year quadrilaterals will be selected for reobservation based largely upon conclusions drawn from the results of prior year's measurements and the total activity indicated by the Geodimeter program. Undoubtedly several sites will be proved inactive after a third or fourth reobservation and will be reobserved less frequently thereafter. However, measurable movement is anticipated at several sites. The program in the future is expected to involve the reobservation of 6-10 figures per year.

Tiltmeters

Because of the low gradient of the Aqueduct (approximately four inches per mile) the Department's Consulting Board for Earthquake Analysis, headed by the late Dr. Benioff, recommended in 1962 that tiltmeters be installed at key Project sites. Later, concern became apparent for the profound effect slight tilting could have on the bearing wear of the Project's large pumps.

Seven, two-component, continuously recording tiltmeters have been installed primarily at pumping plant sites, Figure 48, Page 100. These instruments, developed for the Department by the Timmin Research Corporation, operate in a field environment of high daily thermal variations. They are of a mercury liquid level type capable of resolving 10 microns of differential movement along a 100-foot horizontal line.

Fortunately, in the Wheeler Ridge area, precise levels had been run several times in previous decades; they indicated that tilting could

be a problem. At seven other pumping plant sites no leveling network existed and the construction schedule did not permit time to determine tilt with new networks.

Tilting of one inch over a 50-foot length during a nominal life of 50 years would result in shortened life of bearings in project pumps and generators.

The prototype model was installed at the crest of Wheeler Ridge near the Wind Gap Pumping Plant site in September 1964. Several modifications of the detection and recording system improved long-term dependability. During the fall of 1965, tripartite tiltmeters were installed at the Badger Hills and Tehachapi Pumping Plant sites. Records to date indicate no significant tilting, although unexplained tilt transients one to two hours long, of about two microns, have been observed at Wheeler Ridge. The tilting of the crest of Wheeler Ridge, at its present slow rate, is less than one inch per 100 feet in 100 years.

Tiltmeter installations at the Oso and Pearblossom Pumping Plant sites and at Devil Canyon Powerplant site were essentially completed in June 1966. The tiltmeters will be left in place to measure rebound during excavation of construction sites and to monitor tilt after construction. Unanticipated changes in required repair schedules caused by small changes in tilt rates would affect water delivery for at least six months.

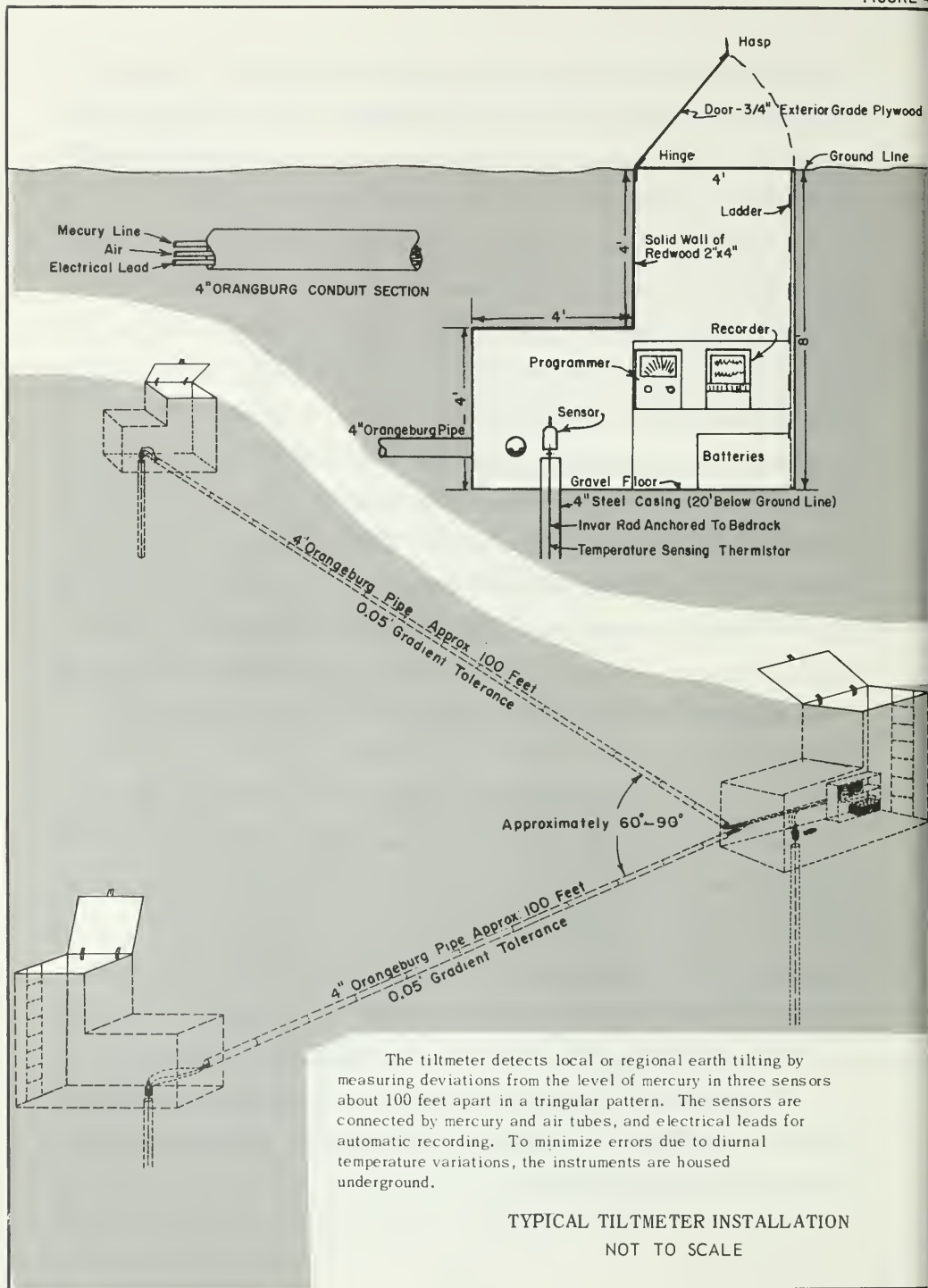
At the Buena Vista Pumping Plant site, rebound from foundation excavation has reached $2\frac{1}{2}$ feet (as measured by leveling and rebound gages). The maximum anticipated was one-half foot. Tectonic stress and gas field recharge are being investigated as possible contributing factors. A Pellissier tiltmeter, recently installed on the active Buena Vista thrust sheet four miles west of the pumping plant, has shown about 400 microns of tilting down in a northerly direction over about 100 feet of base line

during the 62 days of available record (personal communication from W. K. Cloud and R. Rigling, 1968). This is the highest rate of tilt measured near a Project facility (equivalent to about six inches over a 100-foot line if continued for 50 years).

Under a cooperative agreement with the U. S. Geological Survey, another type of tiltmeter has been operated at the base of Wheeler Ridge near the site of the Wheeler Ridge Pumping Plant. It verified old leveling which indicated differential settlement from subsidence and tilting of the valley floor downslope from Wheeler Ridge. The U. S. Geological Survey installation is a combination of compaction recorders and tiltmeters which measure tilting of the ground surface, differential settlement at depth and consequent differentiation between deep and shallow subsidence. The instruments include a water-tube tiltmeter, designed by F. S. Riley, at the surface and invar wires anchored in holes 150 feet deep. The instruments record surface tilting, differential movement between surface piers and deep anchors at the 150-foot level, and the net movement or "tilting" at the 150-foot level.

Mr. Riley's open-file report entitled, "Progress Report on the U. S. Geological Survey Tiltmeter Station Near Wheeler Ridge, California", indicated a further verification of tilting due to subsidence as a function of seasonal water well pumping from deep aquifers. Construction in this area is being preceded by "preponding" to consolidate soils which cause shallow subsidence. Severe tilting caused by the adjacent preponding activities and construction activity in the area necessarily terminated the measurements.

A diagram of a typical tripartite mercurial tiltmeter installation appears in Figure 46. Figure 47 shows installation in progress and Figure 48 indicates locations of tiltmeters.





Construction of a tiltmeter vault at the Pearblossom Pumping Plant site. Three such underground vaults are connected by 4" fibrous pipe carrying mercury, electric and air lines. Beneath the vaults are monuments of invar (low-thermal expansion) rod, anchored firmly in rock or soil 20 feet below ground level. Tiltmeter sensors mounted on the monuments measure differential level changes in microns (0.000039 inch).

Figure 47. TILTMETER CONSTRUCTION

TILTMETER LOCATIONS F.Y. 1965-67

LEGEND

- STATE WATER PROJECT
- - - ACTIVE FAULTS
- ▲ DEPARTMENT OF WATER RESOURCES
- △ FORMER USGS

BADGER HILL

WHEELER RIDGE

TEHACHAPI

OSO

PEARBLOSSOM

CEDAR SPRINGS

DEVIL CANYON

SCALE OF MILES
0 30 100

CHAPTER V: COLLECTION AND ANALYSIS OF DATA ON OTHER EARTH MOVEMENTS

Precise Leveling

There are two major categories of leveling activities pursued as part of the Department's geodetic program:

- (a) subsidence leveling--periodic releveling to monitor land subsidence, and
- (b) control leveling--precise leveling for design and construction of the State Water Project. These have provided, in addition, data concerning vertical ground movement.

Most of these precise leveling activities have been accomplished by U. S. Coast and Geodetic Survey personnel under the Federal-State Cooperative Agreement for Geodetic Surveys and Seismological Investigations. The cost of all precise leveling accomplished under this agreement has been shared equally with the USC&GS, with the exception of a few relatively minor instances where the work has been of singular interest to the Department. Precise leveling is also accomplished by Department personnel to determine ground movement and for special surveys of lesser scope.

Subsidence Leveling

The Department has cooperated with the USC&GS for many years in sponsoring and sharing the cost of periodic releveling in the areas where subsidence is a major problem in the planning and design of water facilities. These areas are shown in Figure 49. Subsidence is caused by compaction of some light porous soils in normally arid areas when they are irrigated, or by compaction of deep pressurized aquifers when water is pumped out more rapidly than it is replenished. Wind erosion of peat soils in some areas



also appears to be a cause. Leveling is concentrated in the San Joaquin Valley where several major subsidence areas have been defined.

Subsidence leveling for the State Water Project consists of a network, bracketed by the California Aqueduct and the Master Drain, extending from the Delta to the vicinity of Wheeler Ridge in Kern County. In Fiscal Year 1965-66, several new lines were added in the vicinity of the proposed Master Drain. Because this is funded from the State Water Project, the portion of the Tulare-Wasco subsidence area east of the proposed Master Drain is not included in the releveing schedule. Funds from other sources will be necessary to provide for future releveing in this area.

Releveing in Fiscal Year 1965-66 extended from Tracy in Contra Costa County southerly to the latitude of Bakersfield in Kern County. Four hundred and fifteen miles of first-order (double run) and 900 miles of second-order (single run) leveling were completed between January and May 1966. Elevations were established for over 1,900 bench marks.

In Fiscal Year 1966-67 the Sacramento-San Joaquin Delta was releveled, verifying the annual 0.1-0.3 foot of subsidence observed over much of this area during the last 50 years. Deep water and gas withdrawal, compaction and peat erosion may all be contributing factors. A special effort will be required to determine which factors are important here. In addition to defining subsidence, this leveling provides up-to-date vertical control for the Federal-State Peripheral Canal and Master Drain.

Most leveling data are evaluated in continuing ground water studies conducted by the Water Resources Division of the U. S. Geological Survey, under a DWR-USGS cooperative contract, and contribute to an understanding of both causes and effects of land subsidence.

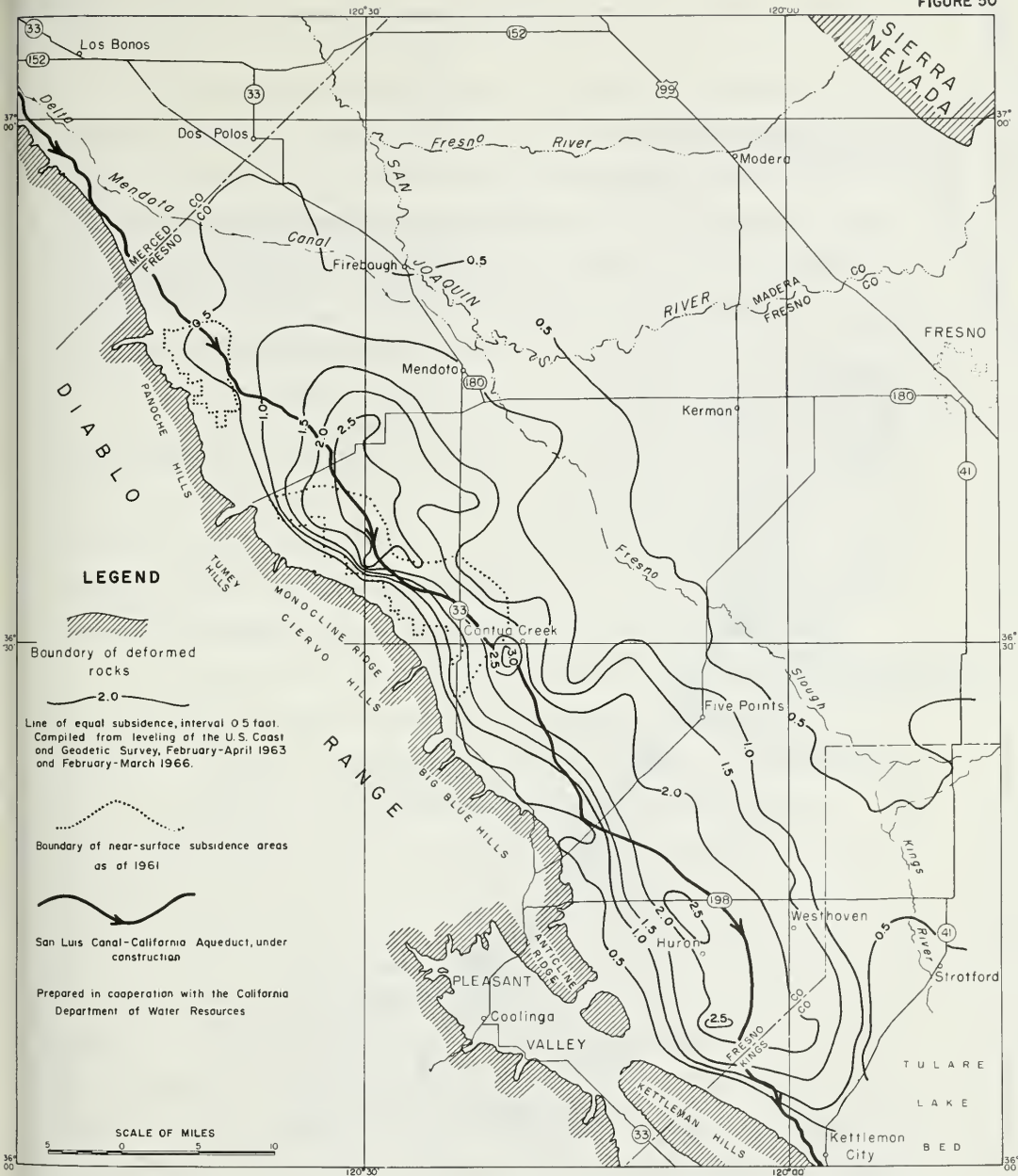
Land subsidence in the Los Banos-Kettleman City area is occurring at a rate in excess of three inches per year over an area of approximately 1,100 square miles. Portions of this area are undergoing subsidence of up to as much as 15 inches per year. Total subsidence in this area is in excess of 20 feet in some locations. Both the California Aqueduct and the Master Drain traverse this area. See Figure 50.

The Arvin-Maricopa subsidence area south of Bakersfield is another area of major concern. The highest rate of subsidence in this area (approximately six inches per year) has occurred just a few miles north of the aqueduct facilities at Wheeler Ridge. Subsidence contour maps indicate that the southerly limit of significant land subsidence in this area is delineated by the White Wolf fault, which acts as a natural ground water barrier.

Control Leveling

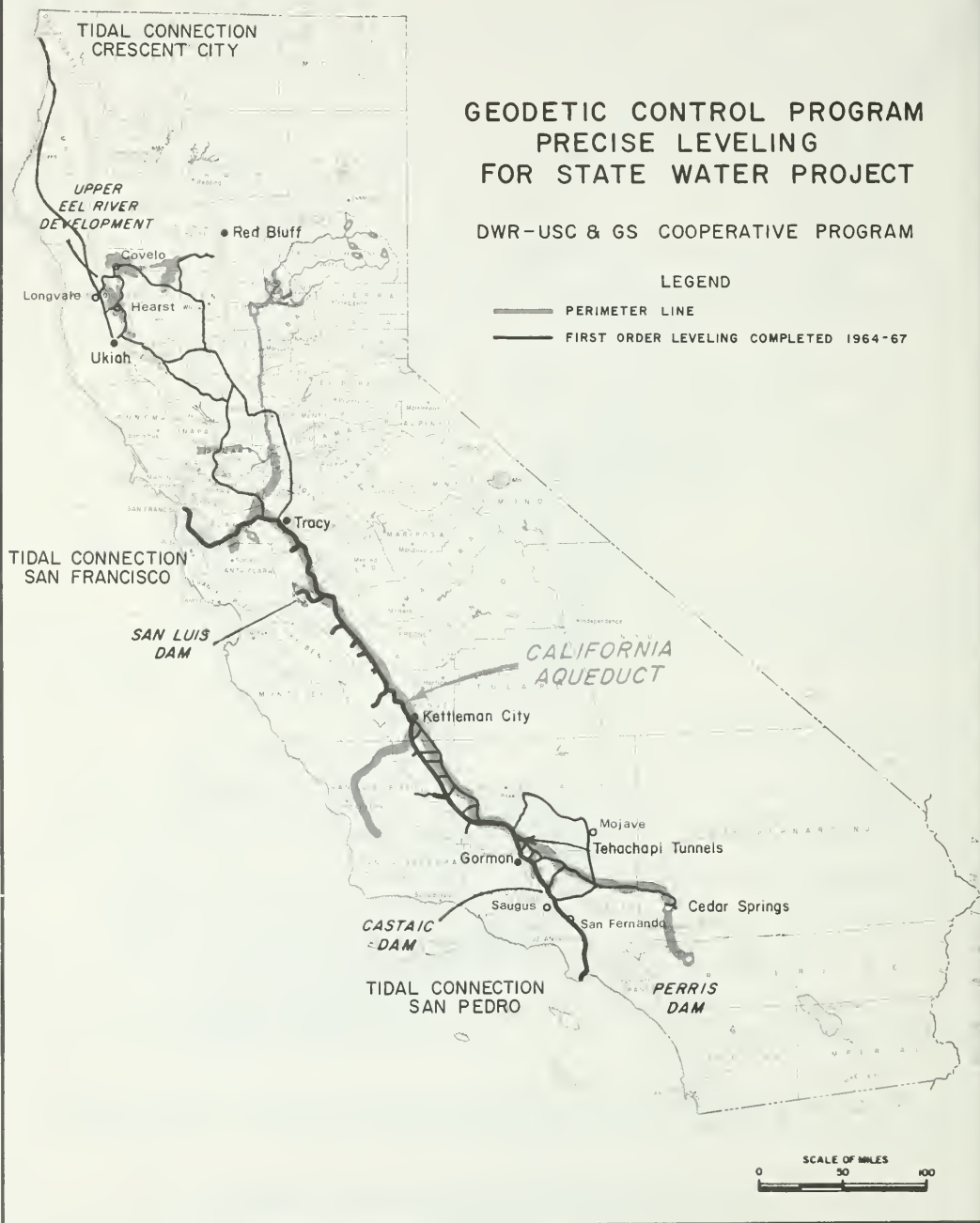
Major cooperative leveling projects were completed during the period June 1963 to June 1967 to provide geodetic survey control for construction of the State Water Project. See Figure 51.

San Pedro-San Francisco. This extensive, continuous line of first-order levels, referred to as the "perimeter line", was formulated for several purposes. For many years, precise leveling to monitor subsidence in the San Joaquin Valley had been tied to selected "anchor marks" located in bedrock at various locations bounding the valley. Leveling activities in connection with aqueduct design and impending construction were also directly or indirectly tied to these same bench marks.



The map shows the amount of land subsidence measured along part of the California Aqueduct. Leveling by the USC & GS and analysis by the USGS under cooperative agreement with the DWR.

LAND SUBSIDENCE ALONG CALIFORNIA AQUEDUCT, LOS BANOS-KETTLEMAN CITY AREA



Some evidence indicated that these anchor marks might have been subjected to movement during past years. The recurrent question of possible tectonic movements in the Wheeler Ridge-Tehachapi area evidenced by unresolved leveling discrepancies precluded final adjustment of a considerable amount of previous leveling in Southern California. Further, construction progress necessitated establishment of grade elevations for the aqueduct between Tracy and the Tehachapi Pumping Plant.

A continuous line of first-order levels was planned from a tide gage connection at San Pedro to a similar tidal connection at San Francisco. The leveling was routed by way of Castaic, Wheeler Ridge, Taft, and along the west side of the valley to the Delta and San Francisco. Between Wheeler Ridge and Tracy, the route was selected as close to the aqueduct as possible to provide accessible stable bench marks for construction surveys.

During Fiscal Year 1963-64, leveling was initiated and extended from San Pedro to Lebec in the Tehachapi Mountains. During Fiscal Year 1964-65, leveling was completed northward to San Francisco. Careful scheduling provided grade elevations as required for construction purposes. Surveys of the Bureau of Reclamation in the San Luis Division and those of the Department in the North and South San Joaquin Divisions were coordinated. As the leveling of the perimeter line progressed, the USC&GS provided tentative adjusted elevations pending complete analysis of the entire line. Later a thorough analysis was made to determine the nature of the network discrepancies in Southern California.

As the leveling of this line progressed northerly from the vicinity of San Fernando the differences determined from field measurements between successive bench marks indicated a gradual increase compared to those from the

most recent leveling and adjustment of this line in 1953-55. At Lebec, near Tejon Pass, an increase of about 0.6 foot had accumulated. Consequently, in the spring of 1965, the portion of the line from Los Angeles to Lebec was releveled for confirmation. The second leveling produced essentially the same result as the leveling a few months previous.

This raised questions concerning the 1953-55 leveling which had been accomplished following the 1952 Arvin-Tehachapi earthquake. At that time a closed loop of levels had been run through Bakersfield, Mojave, Saugus, and Lebec. Since a sizable portion of this loop had just been re-leveled (a portion of the perimeter line and releveled within the Arvin-Maricopa subsidence area during February 1965), it was considered essential to again close this loop in order to provide comparative data for a more complete analysis. Leveling was then extended from the vicinity of Saugus via Palmdale and Mojave to close the loop near Caliente east of Bakersfield.

All field work on the perimeter line and those lines included in the overall evaluation and subsequent adjustment was completed in June 1965.

Analysis of these data together with several thousand miles of additional leveling completed by the USC&GS in Southern California since 1960 resulted in a comprehensive reevaluation and readjustment. Final elevations resulting from this adjustment were available in December 1965. Analysis and interpretation of these data with respect to long-term ground movement is in process by both the USC&GS and the Department.

It is believed that at least a portion of the Tehachapi discrepancy may be due to the adjustment treatment given the 1953-55 leveling. It must be realized, however, that determining the cause of a few tenths of a foot discrepancy in several hundred miles of leveling is

a challenge. Some gradual uplift of the mountain block in this faulted region is certainly not impossible. (The Arvin-Tehachapi earthquake of 1952 raised bench marks in a line of levels over the Tehachapi Mountains from 0.2 foot near Gorman to 2.0 feet at the White Wolf fault.) Evaluation of this leveling resulted in some adjustment to bench mark elevations in the South San Joaquin Valley. There were no changes in basic bench mark elevations north of McKittrick in Kern County.

During 1964, first-order vertical control along the aqueduct alignment from the vicinity of Kettleman City to Taft, was accomplished concurrently with the perimeter line leveling by the Coast and Geodetic Survey under a cost reimbursable agreement. Included were several east-west connections to the perimeter line to provide loop closures.

The result is precise geodetic control for the State Water Project, a considerable upgrading of vertical control throughout Southern California by the Federal Government, and a stronger basis for future determination of vertical ground movement in this area.

Gorman to Cedar Springs Reservoir Site. This line was established (first-order) by the USC&GS in March 1960 under a Department service agreement. The line was established as close as possible to the proposed route of the East Branch Aqueduct through Antelope Valley from the south portal of the Carley V. Porter Tunnel to the Cedar Springs Reservoir site to provide vertical control for project survey activities. Because there were few historic leveling data in Antelope Valley, this line was scheduled for re-leveling in 1964 to determine whether there were indications of subsidence along this portion of the aqueduct route. In addition, the 1960 leveling

did not agree well with first-order cross lines near Palmdale and Hesperia. The releveing provided additional support for the adjustment of the perimeter line and other related leveling in this area.

The portion of the line from Gorman to the vicinity of Palmdale was run in September 1964; the remainder to Cedar Springs Reservoir was completed in April 1965.

Comparison of the 1960 and 1964-65 leveling indicates small random differences of a few hundredths of a foot but no significant differences which could be definitely ascribed to ground movement.

Vicinity Tehachapi Tunnels. In April 1961, the Department contracted with the USC&GS to establish first-order leveling for vertical control in the vicinity of the Tehachapi Tunnels. This work consisted of leveling from Grapevine to the vicinity of the Tehachapi Pumping Plant, thence via Pastoria Creek to the north portal of the Carley V. Porter Tunnel, west along the Garlock fault zone to Lebec and Grapevine to form a closed loop. Leveling was also run southerly via Gorman to the south portal of the Carley V. Porter Tunnel and to a connection with the Gorman to Cedar Springs leveling.

During the summer of 1964, this loop was releveled, primarily to determine if any appreciable vertical movements might have taken place during the preceding three years. Also at this time a new line was run from the north portal to the south portal of the Carley V. Porter Tunnel.

In April 1966, Department survey personnel experienced difficulty in obtaining precise closures between portions of this loop. Releveling by the Coast and Geodetic Survey was arranged and completed in May 1966

In addition, a new line of first-order leveling was established from the Tehachapi Pumping Plant via the discharge lines and Tunnels 1-3 to close a second loop at the north portal of the Carley V. Porter Tunnel. The adjustment of this leveling was completed and final elevations provided. Small random displacements of a few bench marks were found but there were no indications of continuing area uplift or settlement.

Precise Leveling for Upper Eel River Development. Initiation of advance planning activities in the Upper Eel River Development required the establishment of up-to-date vertical geodetic control in this region. This leveling was also necessary to provide a basis for subsequent study of vertical ground movements in this region, where very little is known of crustal movements.

A program was formulated to provide control in the vicinity of the proposed Middle Fork Eel facilities, with connection easterly to the Glenn Reservoir Complex and southerly to tidal observations and to the subsidence leveling net in the Sacramento-San Joaquin Delta.

Precise leveling in the Upper Eel region was originally scheduled to begin during Fiscal Year 1964-65. However, inclement weather and the urgency of resolving problems with the perimeter line and the added Gorman to Cedar Springs work needed for construction caused an unavoidable delay.

Initial work on the Upper Eel Project began in July 1965. Leveling between Hearst and Covelo, through the proposed English Ridge site with a connection to the existing first-order line at Willits, was completed during July and August 1965. During the period May-July 1966, first-order leveling was extended from the vicinity of Ukiah and Longvale on U. S. Highway 101

northerly and easterly through the Dos Rios, Spencer, and Paskenta-Newville reservoir sites, to a connection with existing first-order leveling in the vicinity of Corning in the Sacramento Valley. Approximately 200 miles of leveling were completed, portions of which were over old second-order lines. The line from Ukiah to Covelo is new first-order leveling over very difficult terrain.

To obtain loop closures, essential to proper analysis and adjustment of high-order control leveling, this work was extended southerly from Ukiah via Clear Lake to a connection with the leveling scheduled in the Sacramento-San Joaquin Delta during the winter of 1966-67. From the vicinity of Elk Creek in the Glenn Reservoir Complex, leveling will be extended southerly to close this loop during the spring of 1967.

The new first-order leveling through the Upper Eel with a connection to tidal observations in the Delta will provide a firm basis for additional leveling which will be required as these projects develop.

Landslide Monitoring

Early in 1966 a landslide investigation was formulated by the Department as a part of the Upper Eel Advance Planning Program. One phase of this investigation calls for determination of rates of movement on certain major slides adjacent to proposed Middle Fork Eel River facilities.

Determination of the rate of movement, its direction, and uniformity over the slide mass, requires highly precise surveys. During the summer of 1966, the Department initiated geodetic surveys on a major slide area covering approximately 1,200 acres bounding Spencer Reservoir site.

Monuments were established and the initial series of horizontal and vertical measurements completed. Annual resurveys are tentatively planned.

CHAPTER VI. EARTHQUAKE HAZARD AND ENGINEERING CRITERIA

This program encompasses preparation of earthquake hazard reports, field evaluation of the effects of earthquakes, and development and evaluation of earthquake-resistant design procedures.

The unparalleled magnitude and importance of many features of the State Water Project, combined with the requirement for maximum safety at reasonable cost, demand that the best possible design methods be utilized. They further demand that improved methods of design and analysis continually be sought. Earthquake engineering, both art and science, is in its infancy. Much structural design is based upon empirical static values which assume a steady application of shear force in addition to normal expected loads to accommodate earthquake stress. Although estimates of dynamic behavior are now being used in design, the need for much more knowledge of actual earthquake motions and of reactions of structures to such motions is acknowledged by design engineers.

California has an accelerating population growth with increasing requirements for water retention and distribution facilities. The increasing numbers of hydraulic structures in growing areas of high population density, and the uniquely high earthquake incidence in California require that structures be able to withstand earthquakes and crustal displacements in order to ensure reliability and protect against catastrophic property damage and loss of life.

In view of the foregoing, it is evident that continuing studies are justified in California for the development of improved methods of dynamic analysis and earthquake-resistant design of hydraulic structures.

Following are the specific objectives of the Earthquake Hazard and Engineering Criteria Program:

1. Evaluate and report on earthquake and ground movement hazards at sites of State Water Project facilities with respect to their planning, design, operation, maintenance, and safety.

2. With the close cooperation and active participation of design engineers, seismologists and other appropriate specialists, continue applied research recommended by the Consulting Board for Earthquake Analysis.

3. Maintain contact with universities and with the state, federal, and private agencies involved in advancing the technology. Incorporate information gained from these sources in appropriate design studies required by the Department.

4. Develop methods to effectively utilize the information provided by the quantitative hazard reports and by the research studies at the universities.

5. Make Engineering appraisals of damage to hydraulic structures caused by earthquakes and ground movements so as to assess more realistically the types of damage which might be sustained by facilities of the State Water Project.

Earthquake Hazard Reports

This activity was initiated to evaluate possible hazards related to tectonic phenomena at State Water Project sites. Reports are prepared on individual sites.

A report typically covers:

1. Locations of nearby faults and areas of crustal uplift, and historical surface deformation as a result of fault movements, uplift, or subsidence.

2. Frequency of earthquakes and their magnitudes and epicenters.

3. Maximum expectable accelerations at the site.

4. Historical intensities, accelerations, amplitudes and duration of shaking during earthquakes. Records are also checked for historical earthquake damage to hydraulic structures, and

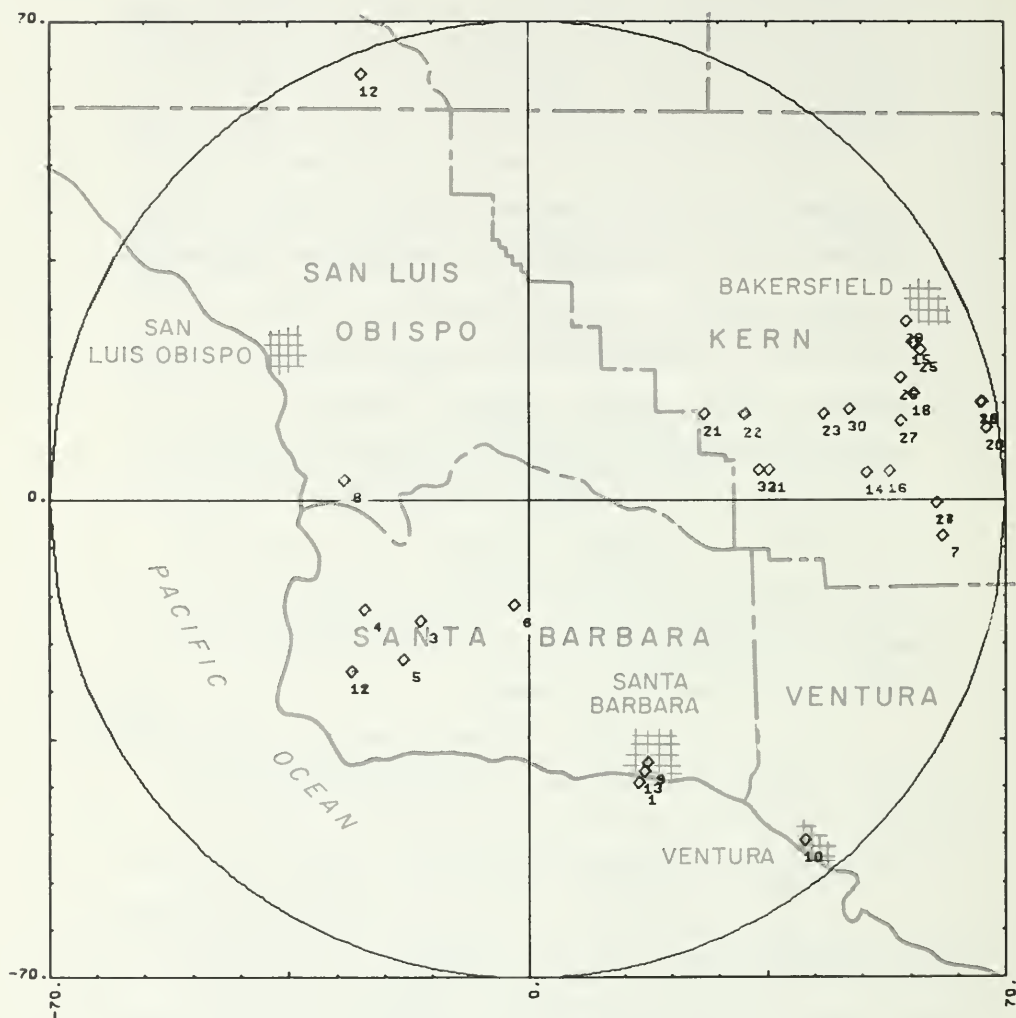
accounts of the secondary effects of earthquakes, including earth lurching, ground settlement, slumping, landslides, mudflows, soil liquefaction and seiches. The probability of recurrence of such secondary effects is estimated.

The rapid construction of the State Water Project required development of an automated system for retrieval of damage data and a program has been constructed for the IBM 7090/7094 computer, based, as noted in Chapter I, on damage to hydraulic structures listed in Bulletin 116-3. Printouts provide locations of damage, distance to epicenters, type of structure, foundation characteristics, intensity, ground acceleration, damage and cost where available and comments by investigating agencies. Damage data can be recalled from storage in a few minutes. Examples of the program output appear in Figures 52 and 53. Each report now requires about one month of a geologist's time, but, if automated, reports can be made available immediately on demand.

Project sites and aqueduct alignments that have been the subject of 23 hazard reports, either prepared or drafted, are identified in Figure 54.

Several of these reports deserve further comment.

The earthquake hazard was a significant factor in the decision to find an alternative to Airpoint Dam, the proposed South Bay Aqueduct terminal storage reservoir near the Hayward fault. Similarly, other hazard reports included information used in relocating or modifying several facilities before final design.



Data on earthquake damage to hydraulic structures, stored on magnetic tape and recalled and plotted by a computer. Within a 70-mile radius of Latitude 35° north, Longitude 120° west, 32 points were plotted where hydraulic structures had been damaged by 11 earthquakes since 1860. Overlapping numbers indicate more than one damaged structure at a single site. A sample printout of the stored data on one of the earthquake and on one case of damage is shown in Figure 53.

COMPUTER-PLOTTED LOCATIONS OF EARTHQUAKE DAMAGED HYDRAULIC STRUCTURES

LATITUDE	LONGITUDE	YEAR	MONTH	DAY	HR	MIN	SEC
35.0	119.0	1952.	7.	21.	11.	52.	14.

MAGN	INT	FOCUS	AREA FELT	NO KILLED	COST	FAULT
7.7	11	-0	160000	12	3700000	WHITE WOLF

WHEELER RIDGE. MAIN SHOCK OF KERN COUNTY SEQUENCE. STRONGEST IN CALIFORNIA SINCE 1906. FELT OVER AN AREA OF 160,000 SQUARE MILES. 12 PERSONS KILLED. MOST DESTRUCTIVE AT ARVIN AND TEHACHAPI. MANY EARTH CRACKS AND LANDSLIDES. CHANGES IN FLOW OF CREEKS, WELLS, AND SPRINGS. SEVERE DAMAGE TO RAILROAD TUNNELS AND TRACKS, AGRICULTURE (IRRIGATION SYSTEMS AND THEN CROPS), OIL WELLS, AND POWER TRANSFORMERS. XI AT BEALVILLE. X ALONG THE WHITE WOLF FAULT ZONE, AND AT EMIDIO, KEENE, OWENS LAKE, VENTUCOPA, AND WHEELER RIDGE. IX AT ARVIN, BUENA VISTA LAKE, CALIENTE AND OTHER CANYONS, CHINA GRADE, GORMAN, KERN RIVER NO. 1, OJAI, MARICOPA, MCKITTRICK ROAD, AND HIGHWAYS 178 AND 466. VIII AT BAKERSFIELD, CAMP SCHEIDECK, CANDIL, COMANCHE POINT, CUMMINGS VALLEY, CUYAMA, GLENVILLE, GOLETA, GRAPEVINE, KERN COUNTY OIL WELLS AND POLE TRANSFORMERS, PALOMA, LYLE CREEK, MARICOPA, MIRACLE HOT SPRINGS, SHAFER, TEHACHAPI, TEJON, WHEELER HOT SPRINGS, WHEELER RIDGE, AND WOODY. VII AT ALPAUGH, BENA, BEVERLY HILLS, BEL-AIR, BUTTOWILL, CALIENTE, CASTAIC, CORCORAN, COMPTON, DI GIORGIO, EXETER, FAIRFAX SCHOOL, FELLOWS, FILLMORE, FORT TEJON, FRAZIER PARK, GLENDALE, GORMAN, HOLLYWOOD, JOHNSONDALE, HANFORD, KEENE, LAKE HUGHES, LAKESIDE SCHOOL, LAMONT, LANCASTER, LEBEC, LORRAINE, LOS ANGELES, MCFARLAND, MARICOPA, MONOLITH, MONROVIA, MT. PINOS, NEWHALL, NORTH HOLLYWOOD, OGDON, OXNARD, PASADENA, PATTIWAY, PORTERVILLE, POSEY, REDONDO BEACH, SAN DIMAS, SANTA BARBARA, SALICOY, SAUGUS, HAIWEE, TUFT, TIPTON, TUPMAN, TWIN OAKS, VAN NUYS, VENTUCOPA, VENTURA, VISALIA, WEED PATCH, AND WOODFORD.

14. LATITUDE	LONGITUDE	NUMBER	56-	2
35 3.5	119 7.3			

WATER PIPELINE	AGE	-0 YRS
FOUNDATION MATERIAL	EPI DIST	INTENSITY
VERY SOFT ALLUVIUM	7	9
		ACC
		-0
		DAMAGE COST
		-0

DAMAGE
1. CRACKED
2. RUPTURED

COMMENTS-

ARVIN-WHEELER RIDGE AREA. THROUGHOUT THIS AREA BURIED IRRIGATION CONCRETE PIPE WAS SHATTERED. IN SOME CASES NEW IRRIGATION SYSTEMS MUST BE INSTALLED. PIPE LAYERS AND CREWS CAME FROM ALL PARTS OF CALIFORNIA AND OTHER SOUTHWESTERN STATES TO AID IN REPAIRING THE EXTENSIVE DAMAGE. NO PARTICULAR BEHAVIOR COULD BE ATTRIBUTED TO VERTICAL STRUCTURES, EXCEPT THAT FAILURE WAS FREQUENT. THE AREAS AFFECTED WERE FOR THE MOST PART NEWLY DEVELOPED LAND. AGE OF INSTALLATION VARIED FROM 5 YEARS TO LESS THAN 1 YEAR NEAR METTLER STATION AND UP TO 15 YEARS SOUTH OF ARVIN. NO SIGNIFICANT DIFFERENCE WAS OBSERVED DUE TO AGE.

Data on earthquakes and on hydraulic structures in California damaged by earthquakes have been stored on magnetic tape. A Model 360 computer was used to recall and print out the data. Figure 52 shows the computer-plotted location of the damaged structure listed above.

COMPUTER OUTPUT OF STORED DATA ON EARTHQUAKE-DAMAGED HYDRAULIC STRUCTURES

EARTHQUAKE HAZARD REPORTS



The report on the Wheeler Ridge Pumping Plant sites, prepared in preliminary form in 1964, was later expanded. Information on earthquakes, faults, and ground movements in the Wheeler Ridge area was presented to a joint meeting of the Consulting Board for Earthquake Analysis and the Tehachapi Crossing Board in May 1965. Data were also included from current Geodimeter, tiltmeter, and precise leveling activities, as well as from vertical and horizontal repeat surveys made by the Department since 1959 and by the Coast Survey since 1932. Later, the data were distributed in the Department in two office reports: "Preliminary Evaluation of the Earthquake Hazard Near Wheeler Ridge" and "Ground Movement and Earthquake Studies in the Wheeler Ridge-Tehachapi Mountains Region".

Reports were prepared during March 1965 on all of the alternative nuclear powerplant sites under consideration by the Department in planning for additional low-cost power for project pumps.

Engineering Criteria

The Department has conducted an extensive program to evaluate earthquake engineering criteria and investigate the applicability of new concepts to design procedures. A number of individual investigations have been conducted and several reports have been prepared by the investigating agencies. Descriptions of these studies, as set forth in these reports, are presented in this section. This presentation makes no assessment of the validity and usability of results of these studies. However, a comprehensive report concerning the interrelation of these studies and their possible significance with respect to earthquake engineering procedures is under preparation. Hopefully, this program will provide better methods of analysis and test these methods by means of actual case studies.

Development of the Program

Design and construction of the State Water Project is a monumental task and would be so no matter where it was built. But to attempt a project of this unprecedented size and complexity in one of the two "most seismic" states in the Union poses additional challenges of unusual magnitude which are being met through a vigorous directed research and development program. The Department early recognized the need for improved methods of analysis of structural and foundation response to large earthquakes, and accordingly the literature was researched and practices of other agencies which have faced similar challenges were reviewed.

The Department followed conventional design practice at the start of this project in 1959, which included insertion of a static force into the stability analysis to represent an earthquake force. This was simulated by an equivalent inertia force equal to some percentage of "g" (the acceleration of gravity). The effect of this force was then assessed in terms of the response of this particular structure.

Lateral force requirements for buildings and related structures have been developed to a high degree of refinement in California. Such provisions are included in "The Uniform Building Code" and in the "Recommended Lateral Force Requirements" of the Structural Engineers' Association of California. However, similar requirements for determining the response of earth structures and foundations to dynamic loads were not available. Conventional design processes in fact were but modifications of structural engineering techniques and were suspected to be, at the best, only a rough approximation of true conditions.

In recognition of the extraordinary seismic hazards that exist in California, Department representatives met with members of the Earthquake Engineering Institute (EERI) in 1960 to discuss what could be done to assure the safety and reliability of State Water Project facilities. The EERI is a group of outstanding authorities in all areas of earthquake engineering which is dedicated to enhancing the safety and efficacy of engineered structures. This group indicated that the field of earthquake engineering was indeed in its infancy, that current aseismic design practices were based to a degree on arbitrary coefficients of questionable validity, and that there was need for development of additional knowledge.

The EERI urged that the Department undertake studies which would provide information badly needed to improve the recognized shortcomings of present design procedures. The Department accepted the suggestion of the EERI and created a Consulting Board for Earthquake Analysis to assist in planning programs to develop the required data and procedures. The Department's present earthquake engineering programs were thus formulated.

In December 1961, with the appointment of the Consulting Board for Earthquake Analysis, an appraisal was made of the seismic design problems of the State Water Project. From time to time since that date, the entire Board or various members as individual consultants have met with Department representatives to discuss seismic problems of both general and specific application.

In November 1962 the Consulting Board for Earthquake Analysis submitted a formal report in which they included:

1. An estimate of the ground movement in the vicinity of the San Andreas fault that may be expected in the event of a great earthquake on that fault.

2. Specification of the general ground shaking, maximum acceleration, and spectrum characteristics that may be expected in the event of a great earthquake on the San Andreas fault.

3. A statement on the behavior of fluid in reservoirs during earthquakes.

4. A statement on the occurrence of landslides during earthquakes. (This described four pertinent types of soil failures and indicated where basic information was lacking.)

5. Recommendations for additional engineering investigations that should be undertaken.

Items 1, 2 and 3 became the basic guidelines for earthquake-resistant design of the State Water Project. Items 4 and 5 became the basis for additional earthquake engineering investigations.

The results of the earthquake engineering research completed or under way are only briefly summarized herein. Detailed information is available in the various references noted in the text. It should be emphasized that the dynamic behavior of conventionally designed embankment structures is not well known. Consequently, the Department's engineering research programs are directed to determine the qualitative and quantitative effects of earthquake shaking on embankment materials and structures. Integrating these and other new techniques into more definitive, universally-applicable, dynamic design procedures remains as a task of no small magnitude.

Strength and Deformation Characteristics of Soils Under Earthquake Loading

An understanding of how soil materials respond to dynamic loads is necessary before the behavior of structures made of these materials can be calculated. This is a soils testing area in which little prior research had been done, other than for some independent studies of repeated loadings, simulating highway conditions, blast resistant design, and design of foundations for vibrating machinery.

Some water-saturated sands and silts have been found to lose all strength and behave like fluids during strong earthquakes. Also some clays suffer large deformations when subjected to the cyclic loading of strong earthquakes.

The phenomenon known as "soil liquefaction" has been encountered with fine-grained cohesionless soils which are both loose and saturated. When such materials in an original loose condition are subjected to pulsating loads, a densification occurs. In fact, vibration is known to be the most effective process for compacting such materials. During the relatively short time of an earthquake, drainage cannot be achieved; and this densification therefore leads to excessive pressure in the pore water which causes the soil mass to act as heavy fluid with practically no shear strength. Ground liquefaction has been noted in a number of earthquakes, especially in the Alaskan earthquake of 1964, the Chilean earthquake of 1960, and the Niigata, Japan, earthquake of 1964. In Niigata the soil lost all strength and the resultant "quick" condition was catastrophic.

Clay-type soils do not exhibit this same behavior, although it has been shown that under similarly repeated cycles of loading large deformations can develop, although the peak strength remains about the same. These deformations can reach the point where, for all practical aspects, the soil has failed.

The Department contracted with the University of California for applied research to determine the factors involved in soil failure. The University's experimental procedures and results are described in the following reports:

1. Seed, H. B., and Lee, K. L. "Studies of the Liquefaction of Sands Under Cyclic Loading Conditions." December 1965.
2. Lee, K. L., and Seed, H. B. "Strength of Anisotropically Consolidated Samples of Saturated Sand Under Pulsating Loading Conditions." July 1966.

3. Peacock, W. H., and Seed, H. B. "Liquefaction of Saturated Sand Under Cyclic Loading Simple Shear Conditions." July 1967.

The university research investigated conditions under which sands can partially or completely liquefy in the laboratory and clays undergo large deformations under loads simulating earthquakes. An approximately linear relationship was shown to occur between the relative density of sands and the stress required to cause initial liquefaction in a given number of stress cycles. At all densities, the cyclic stress required to cause initial liquefaction in a given number of stress cycles increased almost linearly with increase in confining pressure. Another significant accomplishment of the research in the soil testing area has been the development of soils laboratory testing equipment in which such cyclic loadings can be simulated in a laboratory and thus soil samples can be tested under a loading pattern representative of earthquake conditions. The University of California at Berkeley has carried this equipment development to a high level of refinement and has assisted the Department in duplicating the equipment and in using the results in design of several features of the State Water Project.

Response of Embankments to Dynamic Loading

A second major category of information resulting from the University studies includes improved understanding of the response of embankment structures to cyclic loading. The studies by the University included initial steps in the development of new design procedures for embankment dams.

Through model studies, the stability of the Oroville Dam and possible resulting deformations during earthquakes were investigated. The results indicate that an earthquake producing a maximum ground acceleration of 0.5g would not adversely affect the integrity of the structure. These results are discussed in a University report by H. B. Seed, "Model Studies of Oroville Dam

During Earthquakes" (February 1963), which points out the difficulty of scaling the influence of pore water pressures during dynamic loading and that model studies of an embankment are not reliable where pore water pressure development is possible. Another report (Martin, G. R. and Seed, H. B. "Dynamic Response Analysis for Earth Dams." August 1965) presents a summary of viscoelastic response analyses for embankments, by analyzing their behavior on the assumption that they act as damped elastic bodies.

Research on the possible application of a mathematical modeling technique known as the "Finite Element Method of Analysis" to a study of the dynamic response of earth masses is set forth in another report (Clough, R. W. and Chopra, A. K. "Earthquakes Stress Analysis in Earth Dams." July 1965). This report discusses a mathematical model of a triangular section of a dam with homogeneous elastic properties subjected to the vertical and one horizontal component of a simulated El Centro earthquake of May 18, 1940. Computed stresses at selected points in the cross section of the model earth dam are plotted at selected intervals of time.

A follow-up report on this research (Chopra, A. K. and Clough, R. W. "Earthquake Response of Homogeneous Earth Dams." November 1965) compares the shear wedge approach with results of the two dimensional finite element method. Critical limitations in the conventional shear wedge method are set forth. It is concluded that the shear wedge analysis overestimates the fundamental frequency of vibration of a dam. Significant normal stress components are shown to develop on both vertical and horizontal planes in portions of the cross section away from the vertical center line; thus, actual strains developed under earthquake excitation are quite different from the pure shear strains assumed by the shear wedge theory.

In order to check out the validity of the dynamic analyses, the use of shaking machines (large eccentric vibrators) by which embankments can be subjected to forced vibrations of known characteristics has been attempted. This development has been needed because it is obviously impossible to await the occurrence of a major earthquake to test out the new theories. These machines, developed at the California Institute of Technology for the Office of Architecture and Construction of the Department of General Services, have been used primarily to induce vibrations in buildings and other structures. In general, these field techniques have not proved to be of great significance on embankments because the total amount of energy which can be imparted into an embankment by even the largest of these machines is relatively small. It is not possible therefore to strain the materials into the plastic range. However, it has been possible to check the validity of the finite element analysis for predicting dynamic response at least in the linear range corresponding to the low energy vibrations, which are excited by these shaking machines. The results are described in a report by G. R. Martin and H. B. Seed, "An Investigation of the Dynamic Response Characteristics of Bon Tempe Dam, California" (September 1966).

The University also conducted research on the interaction between dams and water in reservoirs during earthquakes. The results of this research were discussed in a report to the Department (Chopra, A. K. "Hydrodynamic Pressure on Dam During Earthquakes." April 1966). The report points out that past and current hydrodynamic design procedures either do not consider the compressibility of water at all or consider it only when the period of excitation is greater than the fundamental resonance period for water pressure. For all reservoir depths, neglecting compressibility of water leads to a response time history identical to acceleration time history. However, the University research indicates that compressibility effects are significant.

New analytical techniques have been developed for studying soil materials in the elastic range. However, most soils when subjected to the very large forces of a strong earthquake would be stressed into the plastic range and would thus behave in a nonlinear fashion. Refinements of the system are therefore necessary in order to permit the use of nonlinear soil characteristics. Also needed in evaluating response of restricted earth masses, such as a high dam in a narrow canyon, is consideration of force and deformation systems to earthquake vibrations in a three-dimensional sense. Such modifications of existing techniques are already in the development stage at the University of California at Berkeley. The ability to predict dynamic response should lead to major advances in the evaluation of stability of embankments during strong earthquakes.

Examination of Contemporary Design Techniques and Previous Embankment Failures

Simultaneously with the study of new methods of predicting dynamic response, consideration was given to surveying all currently existing aseismic design methods. The purpose was to observe the strengths and limitations of each of these methods and to appraise the validity of the results.

At the University, the results of conventional pseudo-static analyses were compared with the recently developed visco-elastic response analysis. The report on this study (Seed, H. B. and Martin, G. R. "The Seismic Coefficient in Earth Dam Design." July 1965) describes in detail the methods of analysis which were compared, and the application and shortcomings of each. Professors Seed and Martin pointed out in their report that the conventional empirical method of selecting a seismic coefficient has little logical basis; it is based on past precedent rather than rational analysis. Several reasons frequently given to rationalize the use of seismic coefficient 0.1g for design purposes are listed in the report. However, the authors show that none appear to be based on logical premise. It appears that repeated use of this coefficient has

given it some semblance of authoritative procedure but no reason for its initial adoption could be found. In a variation of this procedure, the seismic coefficient is assumed equal to the maximum anticipated ground acceleration resulting from an earthquake shock in the area of construction. This approach, which assumes that the dam behaves as a rigid structure, is more conservative and often leads to designs with prohibitively flat slopes. In consequence, a compromise value is often selected. The authors have studied other proposals by different investigators and have found that a wide range of values have been proposed.

It has been demonstrated that by applying these new analytical concepts and the new soils laboratory testing procedures, what might be called the "unsafety" of Sheffield Dam can be predicted. This was a small water supply dam which failed during a very small earthquake near Santa Barbara in 1925. The use of conventional methods of analysis indicates that this dam should have been a safe structure under the probably rather minor shaking effects. Heretofore, this failure had not been adequately analyzed in light of the effects of dynamic cyclic forces. A number of analyses have now been made using data from both cyclic-loading triaxial shear tests and cyclic-loading simple shear tests. The end result of this study is expected to be a demonstration that, by applying these new analytical concepts and new laboratory testing procedures, Sheffield Dam would have been considered unsafe. A report on the study is being prepared.

Dr. James L. Sherard, under contract with the Department, conducted a study to develop presently pertinent information relating to the design of embankment type dams under seismic loading. His report (Sherard, J. L. "A Study of the Influence of the Earthquake Hazard on the Design of Embankment Dams", July 1966) presents the views of many specialists and authorities in various technical disciplines on the seismic considerations associated with embankment dams. Thus, it gives a cross-sectional view of a very difficult

problem as discussed by members of the various professional disciplines with the author. The report presents possible types of damage or failure by earthquake action and discusses ground motion considerations for which a dam should be designed. The effects of faults in dam foundations and large landsliding into reservoirs are discussed.

Studies in Progress

Increased Capability of the Finite Element Embankment Design Program.

Analytical studies of the dynamic response of earth dams are continuing at the University of California. A new eigenvalue program for determining mode shapes and frequencies has been written which will permit an increase in the number of degrees of freedom in a finite element analysis from 140 to possibly 500. This increased capability will make possible the evaluation of the effects of cores and other zones in earth dams, and also the interaction effects between earth dams and their foundations. A report prepared for the Department (Dibaj, M. and Penzien, J. "Dynamic Response of Earth Dams to Traveling Seismic Waves." August 1967) indicates that the dynamic response programs have been modified so that the input ground motion can be represented by a traveling wave as well as by rigid body foundation motion, which has been the case until now. Studies of parameters such as cohesion, shear modulus, shear strength, void ratios, etc., are being carried out with the above programs. Significant contributions can be expected now that real ground behavior and real soil characteristics can be incorporated into the study.

Improved Methods of Computation of Lateral Soil Pressures on Rigid

Structures. This study was initiated originally in support of the structural design of the Tehachapi Pumping Plant, and a usable but approximate analytical solution was developed. Usable design charts were prepared, but these have limitations which prevent general application throughout the project. These

were specifically limited to low values of the so-called "seismic coefficient". Refined mathematical treatments, involving use of the finite element techniques, are being explored so that a solution can be made universal in application to either power and pumping plants.

Cracking Potential in Earthfill Dams. A study has been initiated of potential cracking in earthfill dams which comes as a consequence of earthquake shaking in various azimuths. Cracking is a problem which is critical in the static as well as the dynamic case. It is believed with a limited amount of effort the present techniques for predicting dynamic response of embankments can be extended to permit predicting those areas in the embankment where cracking could be expected as a result of the development of tension fields.

Specialized Training

A very significant contribution to the safe design and construction of the State Water Project has been the availability of specialized training for Department personnel by the faculty of the University of California at Berkeley. In addition to those programs which have been sponsored by the Department, other studies in this field have been underway on the Berkeley campus for some years under the sponsorship of several State and federal agencies. The amount and variety of available professional talents have permitted the development of well-integrated training courses. These include the latest testing techniques, methods of analysis and theories of earthquake-resistant design. Courses presented at Berkeley were repeated in follow-up sessions at Sacramento using as instructors the students who participated in the University's training courses. These were supplemented by seminar sessions conducted by individual consulting engineers and by publication of appropriate technical memoranda and instructions.

Estimates of Earthquake Strong-Motion (Design Earthquakes)

A complete analysis of the reaction of embankment structures to

earthquake shaking requires that characteristics of the shaking be known. These are recorded directly by strong-motion seismographs. However, to date no strong-motion record has been obtained for a near maximum earthquake ($M = 8$). Consequently extrapolations from records of smaller earthquakes and theoretical estimates are used.

Design factors for the Department's hydraulic structures are currently based on acceleration estimates developed in 1962 by the late Dr. Hugo Benioff, then chairman of the Department's Consulting Board for Earthquake Analysis. The analysis, discussed in the November 19, 1962, report on the Consulting Board for Earthquake Analysis, is for the San Francisco earthquake of 1906, which is regarded as representative of the largest earthquake to be expected on the San Andreas fault. The following is an excerpt from that report:

"Permanent displacements of the ground have been observed subsequent to large earthquakes such as San Francisco 1906 and El Centro 1940. Unfortunately, ground accelerations at a point immediately adjacent to the slipping fault have not been recorded, the closest recording being that of El Centro 1940 which was approximately five miles from the fault. Consequently, the ground accelerations adjacent to a slipping fault are not precisely known. The nature of this time-varying ground motion has been postulated by the late Dr. Benioff to be as set forth below.

"In the immediate vicinity of the fault the ground motion consists of a sudden heave or throw corresponding to the fault slip plus relatively weak oscillatory wave movements arriving from distant segments of the slipping fault. The oscillatory waves are presumed to be small because they are radiated at grazing incidence to the slipping fault surfaces whereas the maximum energies are radiated at 45° and 90° to the fault plane for the P and S waves respectively. In the San Francisco 1906 earthquake on the San Andreas fault the relative slip was 21 feet in the middle of the active segment and it tapered off toward the ends. Since the elastic characteristics of the rock on the two sides of the fault cannot differ greatly we may assume that the throws on the two sides were the same and equal to 10-1/2 feet. Presumably the 1857 earthquake on the southern segment of the San Andreas fault produced movements of the same size. Although the slip on the San Andreas fault is primarily horizontal, vertical movements of the order of 2 or 3 feet occur occasionally along with the horizontal movements from warping and nonuniform horizontal slip along the fault. In the 1872 earthquake in Owens Valley the vertical component of slip was about 20 feet and the horizontal somewhat less. On other smaller faults in the State the observed slip has not exceeded about 4 feet.

"Figure 1 [55] shows the configuration of the ground displacement in centimeters as a function of distance from the fault X in kilometers just prior to the San Francisco 1906 earthquake (after Byerly and de Noyer). The y-axis represents the fault. During the earthquake the two halves of the curve separated at the origin and each became straight and colinear with its 305 cm and -305 cm asymptote respectively. The fling displacement y in centimeters as a function of horizontal distance from the fault X in kilometers is thus given by the equation

$$y = 194 \cot^{-1} \sqrt{3.25 \times 10^{-6}} X \quad (1)$$

The corresponding shear strain in the vicinity of the San Andreas fault just before the San Francisco 1906 earthquake is shown in Figure 2 [56] as a function of the distance from the fault in kilometers. The figure also represents the shear strain increment experienced during the earthquake by the ground as a function of distance from the fault. The equation for the shear strain is

$$\sigma = \frac{6.3 \times 10^{-4}}{1 + 0.11X^2} \quad (2)$$

where X is in kilometers.

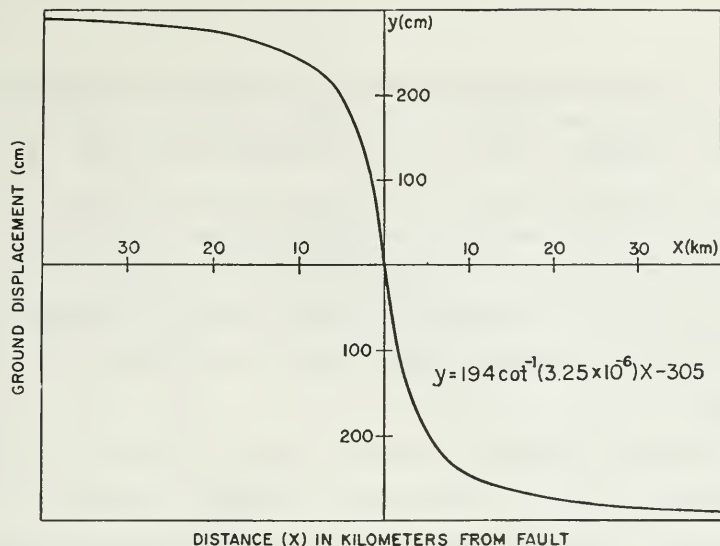
"The character of the fault slip as a function of time has not been observed in any earthquake. From indirect evidence it is inferred that at any point along the fault it has the approximate form of a critically damped oscillation

$$Y = A\sqrt{1 + (\omega t)^2} e^{-\omega t} \quad (3)$$

In this equation the origin of coordinates is taken in the original unstrained configuration. A is one-half the total relative offset and $\omega = \frac{2\pi}{T}$ where T = period. At the time t = 0 when the fault begins to slip the displacement $Y_0 = A\omega^2$.

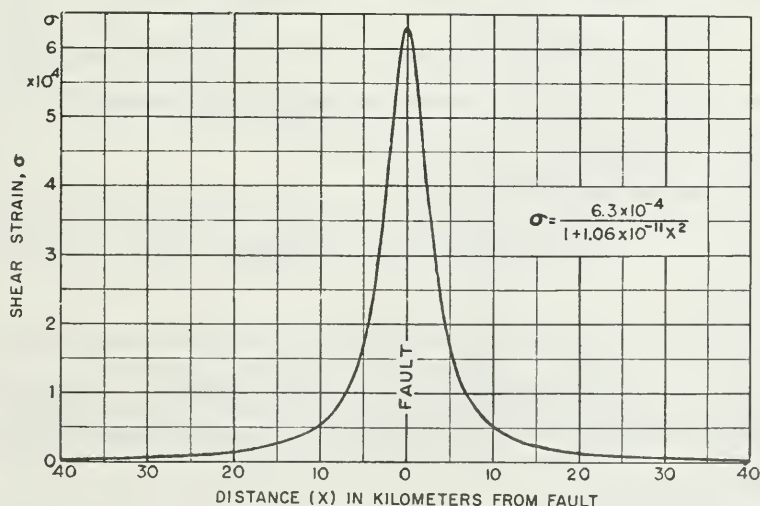
"In the San Francisco 1906 shock A was 305 cm and T is estimated to have been 5 seconds. For these values Equation (3) gives a maximum acceleration of $305 \times \frac{4\pi^2}{25} = 480 \text{ cm/sec}^2$.

Equation (3) thus indicates that the slip started suddenly with an acceleration approximately one-half of the acceleration of gravity and the movement was completed in about 5 seconds. For points away from the fault the throw displacement and acceleration decrease with distance approximately in accordance with equation (1). On the other hand the oscillatory movements are presumed to have a corresponding increase with distance from the fault. The total acceleration is thus roughly constant to a distance of about 12 miles and from there out it decreases. The acceleration associated with the heave of the fault is unidirectional and except in unusual circumstances would not be as damaging as an oscillatory acceleration of equal amplitude. For extremely brittle structures damage from the two kinds of acceleration approach equality but for the average structure damage occurs in the nonlinear range of stresses and in this range oscillatory movements are much more effective."



The relation of ground displacement to distance from a fault just prior to an earthquake of the 1906-type according to the theory of elastic rebound. Assume that the y-axis represents the fault. During the earthquake, the two halves of the curve separate at the origin and each become straight and colinear with its 305 cm and -305 cm asymptote respectively. The fling displacement "y" in centimeters as a function of horizontal distance "x" in kilometers from the fault is represented by the equation in the figure.

Figure 55 GROUND DISPLACEMENT VS. DISTANCE FROM SAN ANDREAS FAULT



Shear strain as computed for the San Andreas fault just before the San Francisco 1906 earthquake is shown as a function of the distance from the fault. Also the shear strain increment experienced by the ground during the earthquake as a function of distance from the fault is given by the equation in the figure.

Figure 56. SHEAR STRAIN, VICINITY OF SAN ANDREAS FAULT

The Consulting Board for Earthquake Analysis also recommended acceleration spectra curves as best current estimates for design of certain structures for a "maximum" earthquake. The spectra were prepared by Professor George Housner at the California Institute of Technology. They are averages derived from several strong-motion seismograms including the east-west component from the 1940 El Centro earthquake. The normalized scale of the spectra, Figure 57, is multiplied by 4 if the effects from a "maximum California earthquake" are desired. The percent of damping of the structure under design must be estimated and the proper curve used.

The Consulting Board for Earthquake Analysis recommended that the Department undertake programs to provide more information on which to base refined estimates. Specific recommendations included the strong-motion seismograph network and the mobile laboratory measurements which have been undertaken by the Department.

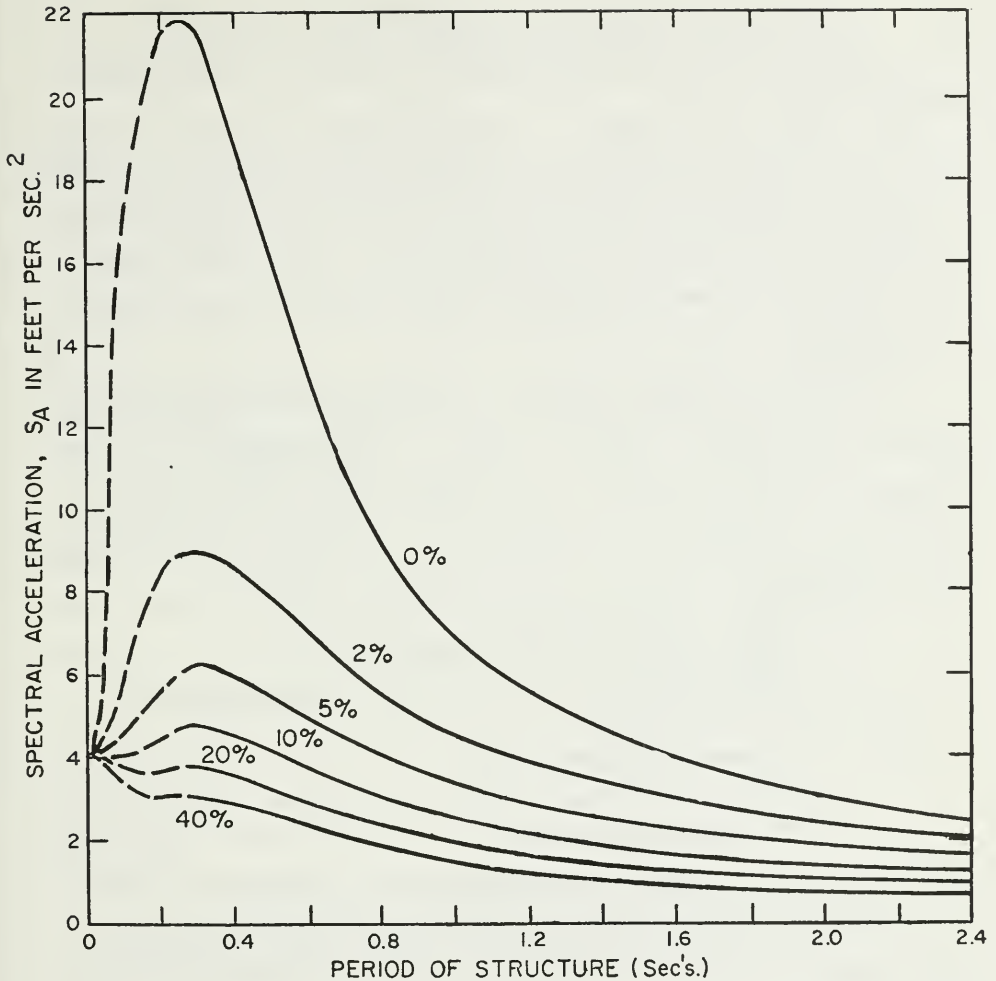
Observational data on ground motions and structural response during strong earthquakes are provided by strong-motion seismographs and seismoscopes discussed under Collection and Analysis of Seismic Data. Processing, storage, and analysis of the strong-motion records -- accelerograms and seismoscope traces -- are provided by the U. S. Coast and Geodetic Survey under a federal-state cooperative agreement.

Acceleration maxima are determined by simple measurements of the accelerogram traces and vectorial addition of the maxima recorded in two horizontal directions.

Predominant periods of the earthquake motion are determined either by an Electric Analog Spectrum Analyzer or by digital computer. Either technique also will yield the energy or amplitude for each of several frequency bands of ground motion.

The determination of ground displacement involves a process of double integration of the accelerogram trace. This has been done several ways including graphical, numerical, and mechanical methods and by digital computer.

FIGURE 57



This family of curves (spectra) is to be used with structures having the indicated percentage of damping to select an acceleration factor required in seismic analysis. This chart was derived by strong motion analysis of available earthquake accelerograms. As the natural period of vibration approaches zero, the maximum acceleration experienced by all structures, independent of damping, is equal to the maximum ground acceleration.

AVERAGE ACCELERATION SPECTRA CURVES

Where applicable and available, ground motion determinations of the U. S. Coast and Geodetic Survey are compiled and included with earthquake hazard reports.

Several of the Department's strong-motion seismographs were triggered during the series of three earthquakes in the Magnitude 5 range at Parkfield, California, in late June 1966. The station nearest the San Andreas fault (250 feet away) recorded accelerations of about $1/2g$, the largest recorded in California.

The collection of earthquake strong-motion records will continue. Meanwhile, three partly theoretical methods are being developed in an effort to provide reliable estimates of ground motions during strong earthquakes which should be anticipated at various sites of State Water Project structures where strong-motion records are not now available. These are.

1. Mobile laboratory comparative measurements.
2. Transfer functions developed between strong-motion records and those of local shocks.
3. Energy distribution estimates.

Mobile Seismograph Laboratories are operated in pairs in each construction site area. They provide spectral ratios of earthquake shaking which provide information concerning how much more a construction site will shake than a hard rock site. During very intense shocks, the amplification factor will differ from the indicated amplitude ratios if the foundation materials do not respond elastically to the intense shaking. Consequently, a data analysis program has been proposed to derive transfer functions between small shocks recorded by mobile or portable seismographs and large shocks recorded by strong-motion seismographs.

The Transfer Function Method involves application of digital filtering techniques to local shock recordings by sensitive seismographs placed at strong-motion recording sites. To provide the data required for analysis, the sensitive instrument must record one or more small quakes which have an epicenter similar to the earthquake recorded by the strong-motion seismograph. This special recording and analysis procedure is repeated at other sites where strong-motion has been recorded. Digital processing techniques are utilized in developing the transfer functions required to derive strong-motion recordings from the smaller shocks. Some historical data have been collected but not enough to thoroughly test the method.

Following the Parkfield-Cholame earthquakes of June 27-29, 1966, a portable sensitive seismograph with magnetic tape recorder was moved to the sites of Department strong-motion seismographs along the Coastal Branch Aqueduct route to record aftershocks. The data are now being analyzed.

Analysis of additional sets of records from other strong-motion seismograph sites will be required before the effectiveness of this method can be evaluated. Comparing the transfer functions will indicate one of three things:

1. All the transfer functions will be sufficiently similar to assume a "universal" transfer function, allowing an estimation of strong-motion from recording of portable seismographs at sites where no strong-motion data exist;
2. Transfer functions will vary from area to area requiring the determination of "regional" functions; or
3. The functions may be so variable that only general information can be derived.

The Energy Distribution Method is based on the concept that, for a given crustal model, energy from a given earthquake will be dissipated or

distributed in a predetermined way between the source and a given point on the earth's surface. If the crust-mantle layering sequence can be determined for the area between a probable earthquake epicenter and a proposed or existing structure, then the strong-motion effects at the structure can be estimated for a given energy spectrum emanating from the epicenter. The analysis process is based on Haskell's solution modified to extend its resolution to higher frequencies.

Development of crustal models required for application of the energy distribution method at Project sites also involves data on lithology and densities of underlying layers, ground water levels, and proximity and configuration of the bedrock-alluvium interface near Project sites.

In their report on "Site Characteristics of Southern California Strong-Motion Earthquake Stations", University of California at Los Angeles Department of Engineering Report No. 62-55 (November 1962), Dr. C. Martin Duke and Mr. David J. Leeds present discussion and data on the application of procedures that are similar to the initial steps in the energy distribution method proposed by the Department.

General data on crustal velocities and layering are available from the U. S. Geological Survey. More detailed data on seismic velocities of near-surface layers are being obtained from petroleum exploration companies. Data on subsurface layering and seismic velocities at State Water Project sites are being developed by the Department. Location coordinates, geographic descriptions, and surficial geologic data are now available for most of the Department's strong-motion stations. Seismic velocity data

are available for: Frenchman, Oroville, Delta Pumping Plant, Del Valle, Buena Vista, Devil Canyon, and Dos Rios strong-motion stations.

Field Evaluation of Earthquakes

Until recently the emphasis of most earthquake investigations has been on damage to buildings in major population centers. The Department's primary interest is the damage sustained by hydraulic structures during major earthquakes. This knowledge is vital to evaluate practices in earthquake-resistant design. For this reason key Departmental personnel are immediately notified of the occurrence of major earthquakes in California. Teams are assigned to investigate areas involving damage to hydraulic structures or other damage of significance to the design and safety of the State Water Project. Such field investigations are coordinated with other agencies to avoid duplication and to provide an opportunity for on-site discussions of the geologic and structural factors which relate to the damage. Frequently, significant damage is repaired in a few hours or days so that quick action by an interdisciplinary group is necessary to obtain an optimum picture of damage sustained.

Hebgen Lake, Montana, Earthquake, 1959

The Hebgen Lake, Montana, earthquake of 1959 was investigated and a 24-page memorandum entitled, "Investigation of the Montana Earthquake of August 17, 1959" was written.

Hollister Earthquake, 1961

When Hollister and the surrounding area was slightly damaged by the earthquake of April 18, 1961, a team was sent to Hollister to investigate and to report on the damage. A memorandum report is on file.

Alaska Earthquake, 1964

A Department team was sent to Alaska for field reconnaissance of damaged areas after the March 27, 1964, earthquake. A summary memorandum was forwarded to the Resources Agency Administrator. Data from the field reconnaissance and from federal agencies, universities, and consultants, were included in Bulletin 116-5, entitled, "The Alaskan Earthquake", published in October 1965.

Corralitos Earthquake, 1964

Soon after the Magnitude 5.2 earthquake of November 11, 1964, near Corralitos, the Geodimeter lines in the epicentral area were measured to determine whether the strain release was detectable. Analysis of field data indicates the possibility of a recurring pattern in pre- and post-earthquake strain changes. The significance of this is included in the discussion of "Earthquake Prediction", earlier in this report.

Seattle Earthquake, 1965

Department personnel investigated the damage caused by the Seattle earthquake of April 29, 1965. An office report entitled, "Seattle Earthquake, April 29, 1965", described the damage and presented recommendations regarding earthquake warnings and investigational procedures of the Department.

Truckee Earthquake, 1966

Department personnel investigated damage. Longitudinal cracking was found along the crest of the Prosser earthfill dam. The dam is about five miles south of the epicenter of the Magnitude 6.5 earthquake of September 12, 1966. Two memoranda were written, "Eastern California Earthquake of 1966", and "Damage to Prosser Creek Dam, California Earthquake of September 12, 1966".

Earthquake Notification

The seismograph station of the University of California at Berkeley notifies Department personnel by phone on an around-the-clock basis when earthquakes of Magnitude 5.0 and greater occur in and near California. Notification of smaller earthquakes is received during office hours. The information is relayed to appropriate Department personnel.

Emergency Plan

A "Department Earthquake Emergency Plan" has been developed. Schedules of action to be taken by repair and operations crews are outlined for various types of possible damage to the Project. Designers and other specialists may be required to participate in investigations for a few days, or as long as several months, depending on the extent of damage.

CHAPTER VII. OTHER EARTHQUAKE PROGRAMS IN CALIFORNIA

Following the 1964 earthquake, President Johnson asked his Science Advisor, Dr. Donald Hornig, what could be done about earthquakes. An "Ad Hoc Panel on Earthquake Prediction" was formed to study the problem of earthquake research. The panel proposed a 10-year, \$137 million research program. Their recommended program would include:

- (1) development of a new generation of instruments for monitoring earthquake faults, including electro-optical distance measuring devices;
- (2) extensive field instrument installations, consisting of "clusters and superclusters" of sensitive seismographs, tiltmeters, strainmeters, magnetometers, gravimeters, meteorological instruments and tide gages, plus special arrays of such instruments in 10,000 foot holes;
- (3) geological and geophysical field surveys of fault zones;
- (4) laboratory and theoretical investigations of rock fracture, creep, and related physical properties of rocks;
- (5) research in earthquake prediction; and
- (6) greatly strengthened research in earthquake engineering.

No funds as yet have been voted by Congress to implement the recommendations, probably because of the serious federal budget obligation posed by defense commitments. Nevertheless, several federal agencies and universities in California have since begun or expanded earthquake prediction studies.

University of California at Berkeley

The University of California at Berkeley began instrumental measurements of earthquakes in 1887 and has since become a world-renowned center of research in seismology and earthquake engineering.

The Seismographic Station of the University is building a multi-purpose geophysical observatory near the San Andreas fault. Basic research at the observatory into the various phenomena associated with earthquakes will include long-term recording of: elastic and acoustic waves, tilt, strain, and conductivity fluctuations as well as variations in magnetic, gravity, and heat fields. Correlations between these parameters and earthquakes will be continuously made.

The observatory is but one of several projects of the Seismographic Station of the University. Operation of its seismograph network and locations of epicenters in North Central California is a continuing program of the Seismographic Station. Nine of the stations in the University's seismograph network are telemetered to Berkeley. The stations were specifically located to straddle the San Andreas fault from Priest Valley to Tomales Bay in order to study aftershock sequences.

The School of Engineering of the University of California at Berkeley is conducting basic and applied research in soils and structural engineering including model studies and cyclic loading tests. These studies are in addition to the investigations contracted for by the Department of Water Resources.

The University of California at Los Angeles

The Department of Geophysics at U.C.L.A. is working on statistical studies of earthquakes to determine the relative significance of possible triggering mechanisms. Studies of the role of water in changing the strength of rocks under pressure are also being conducted.

The Department of Engineering research in earthquake engineering includes: effects of characteristics of site and structure on patterns of damage in past earthquakes; soil and structure dynamics and interaction; development of design methods for nuclear reactors and components subjected to earthquakes, etc.

The University of California at La Jolla

The University of California at La Jolla is working on the development of an inertial reference frame which will measure net displacement along a fault during an earthquake. They are also studying the relationship between seismic noise and ocean swell.

California Institute of Technology

The California Institute of Technology, in November 1966, received a \$407,000 research grant from the National Science Foundation to begin studies of earthquake engineering problems. Dr. George W. Housner, Professor of Civil Engineering and Applied Mechanics, will direct studies such as the following: (1) how the ground shakes during destructive earthquakes; (2) the influence of different kinds of soil on such shaking; and (3) how buildings behave when subjected to earthquake-induced stresses and strains. Research plans call for developing new instruments to record strong ground and building motion, for shaking model structures, testing different soils, and generating artificial earthquakes to speed the production of data.

The Seismological Laboratory at California Institute of Technology is conducting the following special studies along the San Andreas fault: mapping of the strain pattern; installation of arrays of special strain meters; recording micro-earthquakes near the fault; and related measurements

of heat flow, elastic properties and density variations of rock. They also operate seismographic stations in Southern California. Telemeter links are being made from some of these to the Seismological Laboratory in Pasadena.

Stanford University

The School of Earth Sciences at Stanford is conducting the following theoretical and applied research in seismology and tectonic movements:

- (1) analysis of crustal strain from geodetic resurvey data;
- (2) monitoring bending along the Stanford linear accelerator by means of a laser system;
- (3) development of an interferometer laser to measure length changes;
- (4) studies of attenuation of seismic waves through the earth and of core-mantle boundary problems;
- (5) cooperative work with the U.S.G.S. involving tilt and strain measurements.

Other State Agencies

Office of Architecture and Construction

The State Division of Architecture in the Department of Public Works was given jurisdiction in 1933 over school construction in California from the standpoint of safety during earthquakes. It obtained this jurisdiction under the Field Act, which became law following the Long Beach earthquake of 1933. That responsibility now rests with the State Office of Architecture and Construction in the Department of General Services. That office sponsors research investigations of various structural aspects of public school construction. The office has sponsored research on wood diaphragms, wood connections, grouted clay-brick and concrete-block masonry,

damping and drift. It sponsored the development of a shaking machine by the California Institute of Technology.

Division of Mines and Geology

The Division has compiled and published reports on the Kern County earthquakes of 1952 and the San Francisco earthquakes of March 1957. In 1964, with the cooperation of Los Angeles County, the Division began to map geologic hazards in urban areas. It also is conducting regional gravity surveys, and participates in field investigations of earthquakes as opportunities permit.

Federal Agencies

Coast and Geodetic Survey

The U. S. Coast and Geodetic Survey, a part of the Environmental Science Services Administration in the Department of Commerce, is responsible at the federal level for the primary horizontal and vertical geodetic control networks in the United States, including arcs of triangulation across active fault zones in California. The Coast and Geodetic Survey began its work in the field of engineering seismology in 1931. Today the Survey operates over 100 strong-motion seismographs in California in addition to those of the DWR-USC&GS cooperative program and provides analysis of strong-motion records. It participates in vibration studies of buildings; conducts field studies of larger earthquakes; prepares catalogs of reports of earthquakes "felt" by observers, and is responsible for the Pacific tsunami early-warning system, with headquarters in Hawaii.

Geological Survey

The United States Geological Survey, under the Department of the Interior, was established by Congress in about 1879, and was assigned the responsibility of geologic mapping of all the United States, including California.

On October 8, 1965, the U. S. Department of the Interior announced the establishment within the Geological Survey of the National Center for Earthquake Research, with headquarters at the Survey's West Coast office at Menlo Park, California. The establishment of the Center was implemented in part by the relocation of the Survey's Branch of Crustal Studies from Denver, Colorado, to Menlo Park. About 20 scientists and technicians were included in the move. Their programs include:

- (1) Detailed profile studies of geologic provinces using seismic refraction equipment, including velocity-depth profiles along the San Andreas fault to provide improved capability of precisely locating epicenters along the fault.
- (2) Portable, short-period seismographs to record earthquake aftershocks.
- (3) An experimental cluster of seismometers installed in a circle centered on Black Mountain near Palo Alto. The output of the seismometers is telemetered to their Menlo Park headquarters.
- (4) Twenty portable seismographs will be used to get a better idea of the seismicity of Central California from the coast to the San Joaquin Valley at the latitude of Hollister.

The U. S. Geological Survey's basic research program on crustal studies using explosion and earthquake seismology is being integrated with a broad spectrum of research in rock magnetism, heat flow, the behavior of rocks under elevated pressures and temperatures, gravity studies, the

physical properties and shock response of rocks along active fault zones, and geologic studies of the tectonics of the San Andreas fault zone.

Earthquake Mechanism Laboratory

The Earthquake Mechanism Laboratory with headquarters in San Francisco was recently established by the Environmental Science Services Administration of the U. S. Department of Commerce. The Laboratory conducts basic research in earthquake studies leading toward earthquake prediction. Included in their basic research is a continuing program to document field evidence of tectonically induced ground cracking and fault movements. They have acquired a site for a multiple-purpose observatory adjacent to the San Andreas fault south of Hollister, where they will conduct research on heat flow, fault noise, deep-hole seismometry, changes in the earth's magnetic field and the seismic velocity through rocks along the San Andreas fault prior to and during earthquakes, etc. The Earthquake Mechanism Laboratory also conducts research for the Defense Department. The research includes an ocean bottom seismograph program and work involving portable seismographs.

Numerous other public and private agencies conduct or sponsor studies of earthquakes and the effects of earthquakes and crustal movements in California. Only the larger public programs have been discussed here.

THIS BOOK IS DUE ON THE LAST DATE
STAMPED BELOW

RENEWED BOOKS ARE SUBJECT TO IMMEDIATE
RECALL

MAY 12 1978

LIBRARY, UNIVERSITY OF CALIFORNIA, DAVIS

Book Slip-53m-10,'68(J404ss8)458-A-31,5

Nº 601047

California. Department
of Water Resources.
Bulletin.

PHYSICAL
SCIENCES
LIBRARY

TC82!
C2
A2
no.116:1

LIBRARY
UNIVERSITY OF CALIFORNIA
DAVIS



